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FORCE MANAGEMENT METHODS TASK II

Volume I. Summary and Analysis Considerations

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Dayton, Ohio 45469-0001

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A state-of-the-art survey was conducted as the initial phase of the preparation of a handbook of methods for accomplishing the force management task imposed by MIL-STD-1530A. TASK II was devoted to the development of improved methods for performing Force Management with special emphasis on the use of mechanical strain recorders, microprocessors, and crack growth gages as data recording devices. This report summarizes the University of Dayton's effort on general analysis of Force Management data. An error analysis model is

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defined in terms of time to a critical crack length. Va~ious aircraft tracking systems are compared.

FOREWORD

The contractor team of the University of Dayton Research Institute, Lockheed-Georgia Company, and Vought Corporation has been conducting a program to prepare a handbook for achieving the force management objectives of MIL-STD-1530A. Task 2 of this program was aimed at investigating improved methods with emphasis on the use of mechanical strain recorders, crack growth gages and microprocessors as the primary data recording devices. This report is Volume 1 of the Task 2 final report and presents the results of the University of Dayton study on analytical considerations in the collection and analysis of force management data.

The program is being conducted under Contract F33615-77-C-3122 for the Air Force Wright Aeronautical Laboratories AFWAL/FIBEC. Mr. Robert Engle is the current Air Force Project Engineer. Dr. Alan P. Berens of the University of Dayton is serving as Program Manager for the contractor team.

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SECTION 1
INTRODUCTION

Force Management comprises those operations of the Air Force Aircraft Structural Integrity Program that must be conducted to ensure damage tolerance and durability throughout the useful lives of individual airplanes. More specifically, force management is the specification and direction of inspections, preventive maintenance, repairs, modifications and damage assessments required to economically prevent structural failure and preserve the strength and rigidity of the individual airframe during its useful life. To meet the objectives of Force Management, a complex system of data collection, processing, and analysis is required to provide the necessary information for planning decisions.

The team of the University of Dayton Research Institute, Lockheed-Georgia Company and Vought Corporation is under contract with the Air Force to produce a handbook for achieving the Force Management objectives. The program is being conducted in three tasks. The first task was a state-of-the-art survey and is fully described in Reference 1. The second task was devoted to the development of improved methods for performing Force Management with special emphasis on the use of mechanical strain recorders, microprocessors, and crack growth gages as data recording devices for the individual aircraft tracking and loads/environment spectra survey functions. The third task will be the preparation of the handbook.

This report presents the results of the Task 2 effort. It comprises three volumes: Volume 1 summarizes the University of Dayton's effort on general analysis of force management data; Volume 2 presents Lockheed-Georgia's work on improved methods in transport/bomber (T/B) aircraft; and Volume 3 presents Vought Corporation's work on improved methods in attack/fighter/trainer (A/F/T) aircraft.

SECTION 2
FORCE MANAGEMENT OVERVIEW

To ensure that the service life capability of an aircraft system is at least equal to its required service life, the Air Force has instituted the Aircraft Structural Integrity Program (ASIP). This comprehensive program was established by AF Regulation 80-13 (Reference 2) and is described in MIL-STD-1530A (Reference 3) and its referenced specifications. The objectives of the ASIP as stated in AFR 80-13 are fourfold:

1) Establish, evaluate, and substantiate the structural integrity (airframe strength, rigidity, damage tolerance, durability, and service life capability) of aircraft structures.

2) Acquire, evaluate, and utilize operational usage data to provide a continual update of the in-service integrity of the aircraft.

3) Provide qualitative information for decisions regarding force structure planning, modification priorities, and related operational and support decisions.

4) Provide basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft systems.

Five general tasks have been defined to accomplish the ASIP requirements for an aircraft system. These are shown in Figure 1. Tasks I, II, and III are intended to provide compliance with the basic structural design requirements of the airplane while Tasks IV and V assess the design capabilities and plan operational and maintenance requirements to utilize the design potential. Task V is defined as the force management task to be performed by the Air Force while Task IV is the design and implementation of the data package which is required by the Task V decisions. Task IV is performed by the airframe manufacturer.

TASKS TO PROVIDE COMPLIANCE WITH BASIC STRUCTURAL DESIGN REQUIREMENTS

TASK I	TASK II	TASK III
DESIGN INFORMATION	DESIGN ANALYSES AND DEVELOPMENT TESTS	FULL SCALE TESTING
ASIP MASTER PLAN	MATERIALS AND JOINT ALLOWABLES	STATIC TESTS
STRUCTURAL DESIGN CRITERIA	LOAD ANALYSIS	DURABILITY TESTS
DAMAGE TOLERANCE & DURABILITY CONTROL PLANS	DESIGN SERVICE LOADS SPECTRA	DAMAGE TOLERANCE TESTS
SELECTION MAT'LS, PROCESSES, & JOINING METHODS	DESIGN CHEMICAL/ THERMAL ENVIRONMENT SPECTRA	FLIGHT & GROUND OPERATIONS TESTS
DESIGN SERVICE LIFE AND DESIGN USAGE	STRESS ANALYSIS	SONIC TESTS
	DAMAGE TOLERANCE ANALYSIS	FLIGHT VIBRATION TESTS
	DURABILITY ANALYSIS	INTERPRETATION & EVALUATION OF TEST RESULTS
	SONIC ANALYSIS	
	VIBRATION ANALYSIS	
	FLUTTER ANALYSIS	
	NUCLEAR WEAPONS EFFECTS ANALYSIS	
	NON-NUCLEAR WEAPONS EFFECTS ANALYSIS	
	DESIGN DEVELOPMENT TESTS	

TASKS TO ASSESS DESIGN AND PLAN STRUCTURAL OPERATION AND MAINTENANCE

CONTRACTOR	USAF
TASK IV	TASK V
FORCE MANAGEMENT DATA PACKAGE	FORCE MANAGEMENT
FINAL ANALYSES	LOADS/ENVIRONMENT SPECTRA SURVEY
STRENGTH SUMMARY	INDIVIDUAL AIRPLANE TRACKING DATA
FORCE STRUCTURAL MAINTENANCE (FSM) PLANS	INDIVIDUAL AIRPLANE MAINTENANCE TIMES
LOADS/ENVIRONMENT SPECTRA SURVEY (L/ESS)	STRUCTURAL MAINTENANCE RECORDS
INDIVIDUAL AIRPLANE TRACKING (IAT) PROGRAM	

Figure 1. USAF Aircraft Structural Integrity Program Tasks (MIL-STD-1530A).

2.1 FORCE MANAGEMENT DEFINITION

The MIL-STD-1530A definition of force management is "those operations that must be conducted by the Air Force during force operations to ensure damage tolerance and durability throughout the useful life of individual airplanes." In an effort to obtain a less qualitative definition of force management consider the following definitions (also from MIL-STD-1530A):

> "Damage Tolerance. The ability of the airframe to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired usage."

> "Durability. The ability of the airframe to resist cracking (including stress corrosion and hydrogen induced cracking), corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a specified period of time."

From these definitions, it is obvious that damage tolerance and durability are structural qualities which are designed and produced into an airframe. Structural tests can measure the airframe damage tolerance and durability by estimating the periods of time required for excessive cracking or failure during a typical usage. It then becomes the task of force management to maintain the structure during its inherent useful life.

Therefore, another definition of Force Management can be formulated as:

> "Force Management. The specification and direction of inspections, preventive maintenance, repairs, modifications, and damage assessments required to economically prevent structural failure and preserve the strength and rigidity of the individual airframe during its useful life."

Thus, while the basic objective of ASIP is to ensure operational safety and readiness of the airframe, the force management objectives are to:

1. Prevent structural failure through an effective maintenance program of inspections, repairs, and modifications.

2. Preserve structural strength and rigidity through an effective preventive maintenance program of environmental protection and economic repair or replacement of deteriorating parts.

3. Minimize structural maintenance costs by eliminating unnecessary structural maintenance actions through effective application of data on test and operational failure modes and data on individual aircraft usage.

The following paragraphs present a brief description of the elements which constitute force management and a discussion of the interfaces between the elements.

2.2 FORCE MANAGEMENT ELEMENTS

To meet the force management objectives, specific contractor and Air Force tasks have been defined in MIL-STD-1530A. These tasks are comprised of the elements listed in Figure 2.

The five elements which constitute the Task IV Force Management Data Package are performed by the contractor to provide the Air Force with the procedures and data required to manage subsequent fleet operations and maintenance. To avoid duplication, the contractor is strongly encouraged to utilize, where possible, government furnished equipment, facilities, and personnel to acquire and process operational data during these tasks. It is intended that performance of Task IV will lead to a smooth transition into the Air Force operation during Task V.

CONTRACTOR	USAF
TASK IV	TASK V
FORCE MANAGEMENT DATA PACKAGE	FORCE MANAGEMENT
1. Final Analysis -Initial Update of Analysis -Final Update of Analysis -Inspection and Repair Criteria 2. Strength Summary 3. Force Structural Maintenance Plan -Initial FSM Plan -Updated FSM Plan 4. L/ESS Data Analysis -Data Acquisition Provisions -Data Processing Provisions -Interim Processing Services -Baseline Operational Spectra 5. Individual A/C Tracking Program -Tracking Analysis Method -Data Acquisition Provisions	1. L/ESS -Data Acquisition Procedures -Data Acquisition Services -Training -Data Processing Services 2. Individual A/C Tracking Program -Data Acquisition Procedures -Data Acquisition Services -Training -Data Processing Services 3. Individual A/C Maintenance Times 4. Structural Maintenance Records

Figure 2. Force Management Elements

The four elements of Task V Force Management are performed by the Air Force to provide maintenance planning and structural integrity information for the remainder of the aircraft service life. The Force Management elements are keyed to the projection of maintenance requirements based on individual aircraft usage and to detect when changes in fleet operation dictate a new durability and damage tolerance analysis and/or review of analytical monitoring procedures developed in Task IV.

The diagram in Figure 3 indicates the relative time sequence of the force management elements.

2.2.1 Final Analysis (Force Management Data Package)

The final analysis will update the design analyses to incorporate the results of the developmental and full-scale tests and, later, to incorporate the baseline operational spectra. These analyses will also develop inspection and repair criteria for use in the force structural maintenance plan.

2.2.1.1 Initial Update of Analysis

During the design analyses, input loads and structural transfer functions are based on accepted analytical procedures and empirical data from wind tunnel or other scaled tests. The final proof of these analyses is the measurement of airframe response to design load conditions during full-scale testing. Because of the time required to fabricate and instrument full-scale test articles and to conduct the required tests, the test results are not normally available until during the production stage of the airframe. This data is used to update the analyses prior to developing the structural maintenance plan.

2.2.1.2 Final Update of Analysis

After the fleet has been operational for a significant period of time, a baseline operational spectra (in the form of stress sequences at critical locations) is derived from recorded operational data. The damage tolerance and durability analysis will be repeated using the baseline operational spectra and this assessment will result in inspection and modification requirements for the airframe and an economic life estimate based on projected wearout of the structure.

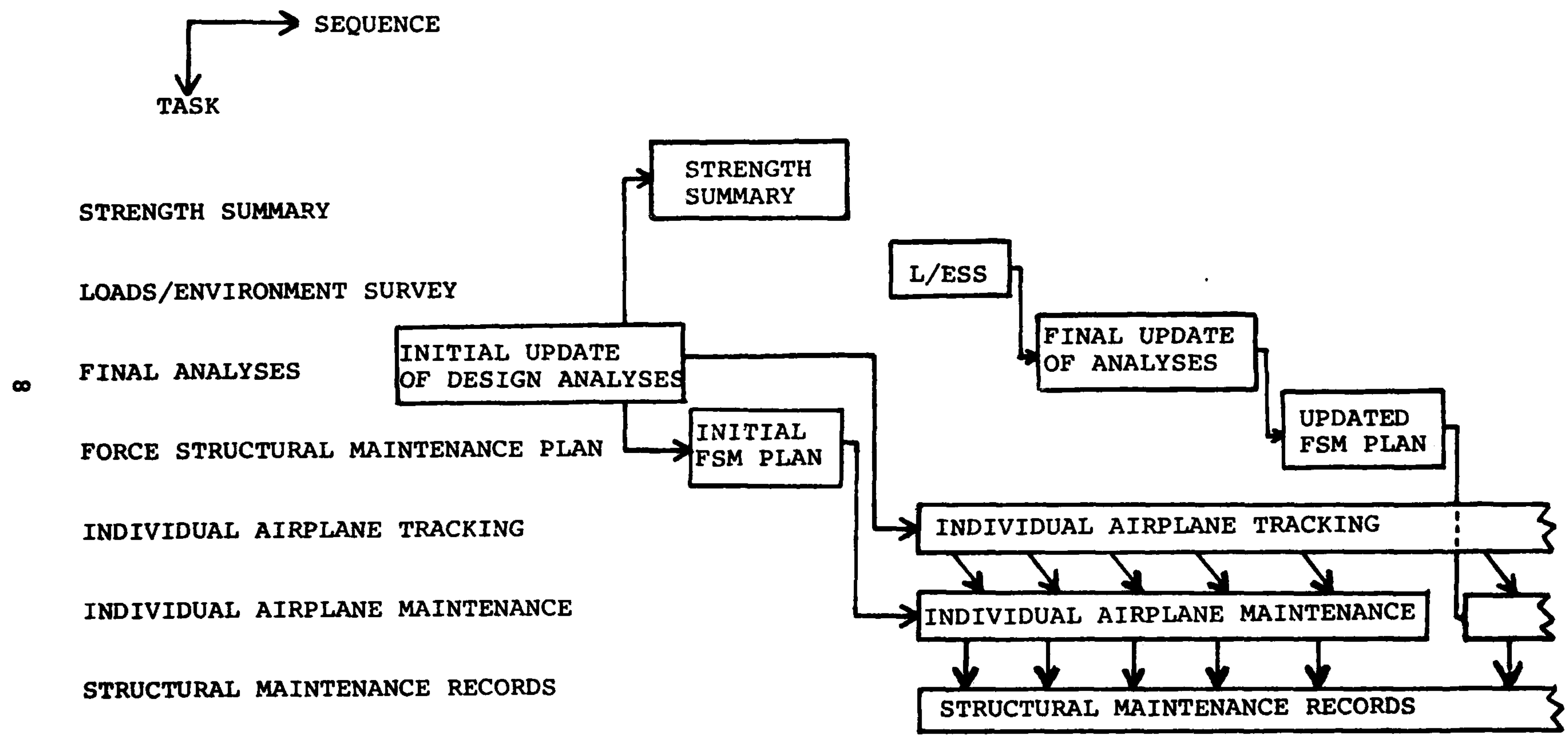


Figure 3. Relative Time Sequence of Force Management Elements.

2.2.1.3 Development of Inspection and Repair Criteria

Based on the analysis, rational criteria must be developed to guide inspection and repair limits and procedures. The criteria must consider types of material and construction, reasonable limits of repair, critical crack lengths, and inspection capabilities to define inspection criteria and repair procedures.

2.2.2 Strength Summary

This summary will indicate airframe limits and capabilities in terms of operational parameters (airspeed, N_z, c.g. travel, and weight). The summary will include a structural description including arrangement, materials, design conditions, damage tolerance and durability critical areas, and margins of safety. Backup documentation will be referenced.

2.2.3 Force Structural Maintenance Plan

The force structural maintenance (FSM) plan shall form the basis for the airframe portions of the TO 1X-XX-6 Aircraft Scheduled Inspections and Maintenance Requirements Manual, the TO 1X-XX-36 Nondestructive Inspection Manual, and the TO 1X-XX-3 Structural Repair Manual. The plan will specify what structural inspections and modifications are required; when they should be accomplished; how inspections, modifications, and repairs should be accomplished; critical structural locations; and cost data for repairs and inspections where trade off decisions may be appropriate. The Air Force will use this plan for budgetary planning, force structure planning, and maintenance planning.

2.2.3.1 Initial Force Structural Maintenance Plan

This plan will be based on the design service life and the results of the initial update of the final analysis.

2.2.3.2 Updated Force Structural Maintenance Plan

This update will be based on the final update of the analysis and the baseline operational spectra. Additional updates will be made any time the force operation uncovers new critical structural areas or significant change in the operational spectra.

2.2.4 Loads/Environment Spectra Survey

Since the actual usage of the aircraft may impose a stress environment different from that predicted during design, an early assessment of the operational usage is obtained through the loads/environment spectra survey (L/ESS). This element of force management consists of monitoring the time histories of the relevant flight parameters during operational flights so that an assessment of stress histories at critical locations can be made. Since the operational usage of an airplane can change, the Air Force also has the responsibility for reinstating (if necessary) the L/ESS and initiating an update of the baseline operational spectra.

2.2.4.1 Data Acquisition Provisions

Responsibility for determining the required parameters to be monitored, the number of aircraft to be instrumented, the length of recording period, and the instrumentation system belong to the airframe manufacturer. Since data acquisition begins with delivery to the Air Force of the first operational aircraft, the L/ESS program should be initiated during the design and development phases. This initial planning will provide an efficient deployment of the sensors and data recording devices on the aircraft. Depending on aircraft type, intended usage, and critical points, the instrumentation system selected may also be used for the individual aircraft tracking program.

2.2.4.2 Data Processing Provisions

The airframe contractor has the responsibility to design a data processing system that is compatible with the Air Force capabilities of the Aircraft Structural Integrity Management Information System (ASIMIS). For the initial L/ESS the contractor is also responsible for performing those aspects of the data processing which are outside the scope of approved capabilities which exist within the Air Force at ASIMIS. The Air Force will perform reformatting/transcribing functions and data editing to ensure the quality of the data.

2.2.4.3 Baseline Operational Spectra

When a statistically adequate sample of data is recorded (representative of the types of usage planned for the aircraft), the airframe contractor will analyze the data and develop the baseline operational spectra. The durability and damage tolerance analyses will be updated using the baseline operational spectra if different from the design spectra.

2.2.5 Individual Airplane Tracking Program

A significant part of force management is the provision to schedule maintenance actions based on the usage of each individual airplane to improve safety and readiness and to reduce costs. The objective of the individual airplane tracking (IAT) program is to monitor the usage of each individual airplane and to provide structural inspection and maintenance schedules based on predicted flaw growth. Provisions will be made to track, in addition to airplanes, major serialized structural components which are likely to be removed, inspected or repaired, and reinstalled on a different airplane.

2.2.5.1 Tracking Analysis Method

A tracking method will be developed which is compatible with the damage tolerance and durability analysis results. The method will determine which airplane usage parameters must be monitored to permit adjustment of inspection intervals and modification and repair times. Since the tracking program will be operated by the Air Force, data processing and analysis requirements must be compatible with the Air Force data analysis system.

2.2.5.2 Data Acquisition Provisions

A data collection system will be selected to monitor and record the required tracking data on each aircraft. The least expensive data collection system which will record the required parameters at the required level of accuracy will be selected.

2.2.6 Individual Airplane Maintenance Times

By using the force structural maintenance plan and the recorded individual aircraft usage data, structural maintenance times will be projected for each airplane.

2.2.7 Structural Maintenance Records

The Air Force will maintain records of significant structural maintenance actions for each airplane. The records will be made available to the airplane usage tracking activity so future maintenance projections can account for previous inspection findings, repair actions, and structural configuration changes.

2.3 FORCE MANAGEMENT OPERATION

During the operational phase of an aircraft system, the interaction between the individual force management elements can be interpeted as in Figure 4. The following description of the force management system assumes that the final analyses are based on stable operational spectra as determined by the L/ESS program. The ASIP Office of Primary Responsibility (OPR) for the weapon system is introduced as the prime recipient of data and the decision maker with respect to maintenance actions and scheduling.

From the viewpoint of the force management process, a key requirement of the Final Analysis is the determination of inspection and repair time for structural components and assemblies based on a quantitative approach. To meet this requirement, the analysis must identify all critical areas as well as the damage limit and damage growth rate in each critical area. Therefore, as part of the durability, and damage tolerance analysis, damage size is calculated as a function of time in representative stress environments. This result is typically viewed as a plot of potential crack length versus "baseline" hours. When the initial crack size is assumed to be the largest that could pass the manufacturer's quality control system, the curve is used to determine inspection limits for safety. Durability is assessed in terms of time required for an average equivalent initial flaw or a distribution of

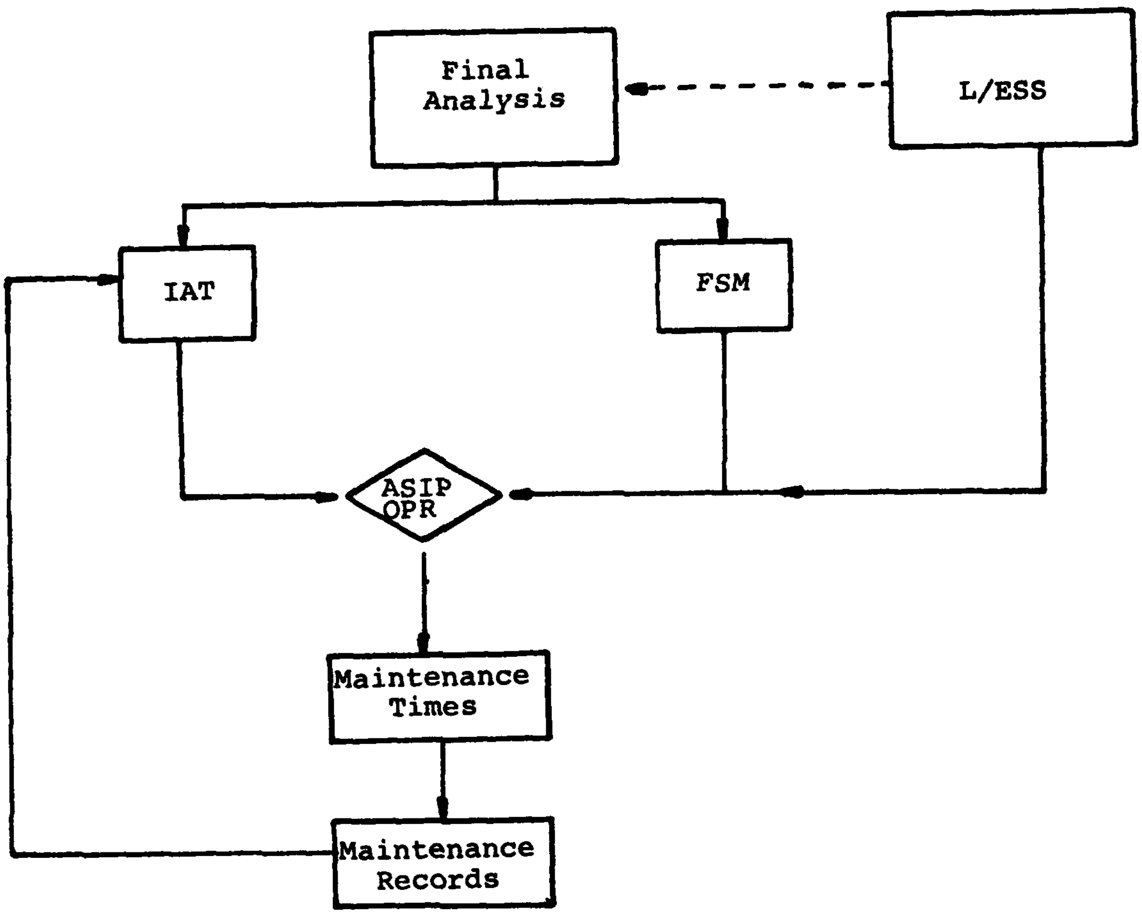


Figure 4. *Flow Diagram for Force Management Operation.*

equivalent initial flaws to grow to a size indicative of widespread cracking (Ref. 4).

A crack length-flight time curve is calculated for each critical area and is based on the operational stress sequences as determined during the L/ESS. Such curves provide basic information required in the development of the Force Structural Maintenance Plan (FSM). They are based, however, on average usage in some stratification of the entire force and, thus, are representative of an average airplane in the stratification. To ensure the integrity of individual airplanes, the Individual Aircraft Tracking (IAT) program monitors the potential crack length at the critical locations based on the stress environment each airplan experiences. While there are many methods for performing the IAT function (Section 3) all require at least some data from the durability and damage tolerance analyses.

The FSM Plan and the IAT results are the primary data sources on which the ASIP OPR makes decisions. The FSM identifies the inspection, modification and cost requirements of the average airframe and forms the basis for maintenance, budgeting, and perhaps operations planning. Output from the IAT program provides the data to schedule maintenance actions or specific airplanes as determined by the growth of potential cracks at the critical locations. Given a maintenance action has occurred, feedback is required to update the maintenance records and to reset (if appropriate) initial crack sizes in the IAT program.

The L/ESS function is shown as meeting two objectives: providing the operational stress sequences which define average usage for the final analyses and providing a continuous base of data to the ASIP OPR in order to detect usage changes and to provide data summaries of flight operations. These data can serve to trigger the need for an update of the final analyses and to identify usages which are particuarily damaging. In the latter case, the ASIP OPR may be able to influence maintenance scheduling by arranging, for example, to have high damage aircraft avoid high damage operations. These topics will be further addressed in Section 4.

This simplified view of the force management plan in operation empahsizes the importance of the Final Analysis. Further, since the FSM is a relatively static set of information, only the IAT has a significant function is supplying information to the ASIP OPR on a continuing basis. While it is recognized that the continuous data from a sample of the force obtained in the L/ESS has non-prime uses, it can also be recognized that such data may not be required for all aircraft types. This topic will also be addressed in Section 4.

SECTION 3
INDIVIDUAL AIRCRAFT TRACKING FUNCTION

The IAT function can be summarized as monitoring the minimum number of parameters in as efficient a manner as possible in order to provide when desired:

(a) an estimate of the potential crack length at each critical location in each airplane of the force, and,

(b) an estimate of the date each aircraft will require a maintenance action based on the calculated crack length and planned usage.

To date, these objectives have been met by correlating the usage parameters of flight hours by mission, flight time by flight condition, stress at a control point, or counts of normal acceleration at center gravity with the crack length versus average usage time curves of the Final Analysis. (The crack growth gage is the new activity indicator currently being considered.) To date, also, each airframe manufacturer has at least one analysis method which provides "sufficiently accurate" results.

This section is devoted to an analysis of the accuracy of tracking systems. First, a definition of IAT accuracy is postulated. This definition is then used to formulate an error model which is exercised using data from an attack/figher/trainer (A/F/T) aircraft. The current analytical methods for tracking crack growth are then compared for accuracy. Finally, since the mechanical strain recorder (MSR) is a relatively new recorder, the reliability observed when this recorder was used on the F-5 A/B Service Life Extension Program is summarized.

3.1 DEFINITION OF ACCURACY

By definition a critical location is one subject to potentially unacceptable crack initiation and growth under the stress environment experienced by the aircraft. During the durability and damage tolerance analysis (DADTA) which is performed for each aircraft type, a model is formulated for each critical location by which the crack length as a function of flight time in an assumed stress

environment could be "best" calculated. This model reflects the analytical capability for calculating crack length. A particular cracked structure experiencing the stress history would not necessarily display the predicted crack length history. Variability in crack growth rate data (from tests), structures, materials, environment, etc. preclude the possibility of being exact for any specific structure and stress environment. Thus, the computional model predicts an average crack growth behavior and reflects only differences that are due to stress sequences.

In IAT, the objective is to track potential cracks. In general, there is not a real crack of the magnitude being tracked. Therefore, the definition is postulated that the perfectly accurate tracking system is that which can reproduce exactly, the output of the "best" computational model of the DADTA. Deviations from this model would be "errors". Note, however, that no measure of the error is available, in general, since the exact stress history at the critical location will not be generally available as input.

3.2 ERROR ANALYSIS MODEL

Discussions of the accuracy of tracking analysis methods and recording devices tend to center around the accuracy of the inferred stresses. In an effort to isolate significant sources of inaccuracy in the product of interest to the ASIP OPR, the following error analysis was formulated. This model predicts variation in predicted calendar time to maintenance action as a function of variability in individual aircraft flying rate, individual aircraft usage severity, and errors in estimated potential crack length. An example is presented using data from a recent IAT update from an A/F/T aircraft.

3.2.1 Background

Two basic data items from an IAT Program are an estimate of the current damage state (crack length) at critical locations of each aircraft and a projection of the time required for these damage states to reach a critical level. Without loss

of generality this discussion will be directed to a single control point and the analysis method for calculating current crack length will not be specifically addressed at this time.

Projections of times to critical crack length are based on an FSM plan assumed usage from which crack length as a function of flight time (in this assumed usage) is calculated. Figure 5 portrays an example of such a basic curve and introduces the following notational concepts:

a_c - critical crack length (however defined)

t - flight time in planned usage environment - also called baseline or equivalent flight time

t_c = planned usage flight time for crack of size a_o to grow to a_c. $t_c = f^{-1}(a_c)$.

The function of f(t) can be used to correlate baseline time between any two crack sizes and, thus, provides the mechanism for projecting planned usage time to critical crack length.

A direct comparison between potential crack growths experienced by individual aircraft is accomplished by referencing all aircraft to the FSM baseline crack growth as shown schematically in Figure 6. At flight time t_i^* of an individual aircraft, the potential crack length at the critical point is calculated to be a_i. For this crack length, the corresponding number of planned (baseline) flight hours is t_i and the remaining baseline hours to critical is given by $t_c - t_i$.

For planning purposes, baseline flight hours until critical crack length must be converted to calendar time. While details of accomplishing this conversion may vary from aircraft type to aircraft type, the basic method is usually modeled in terms of planned flight hours per month and a usage severity factor which reflects known differences in planned usage for various stratifications (e.g. command by base) of the fleet.

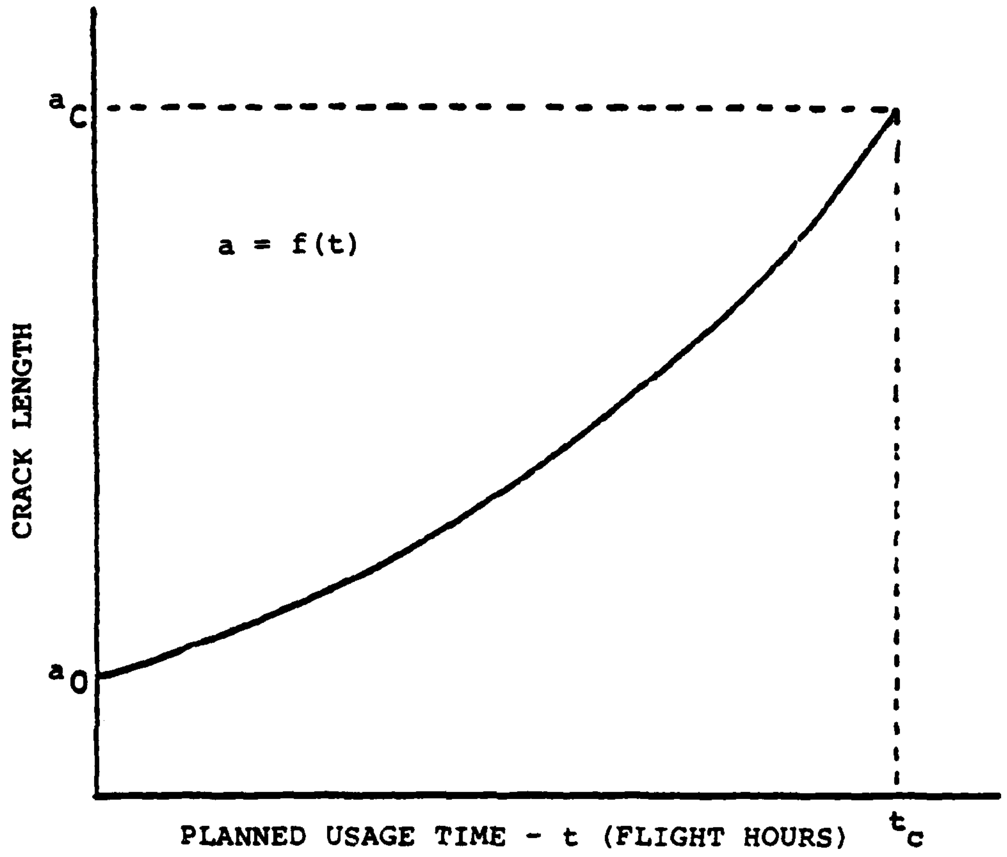


Figure 5. Crack Length as a Function of Planned Usage Flight Time.

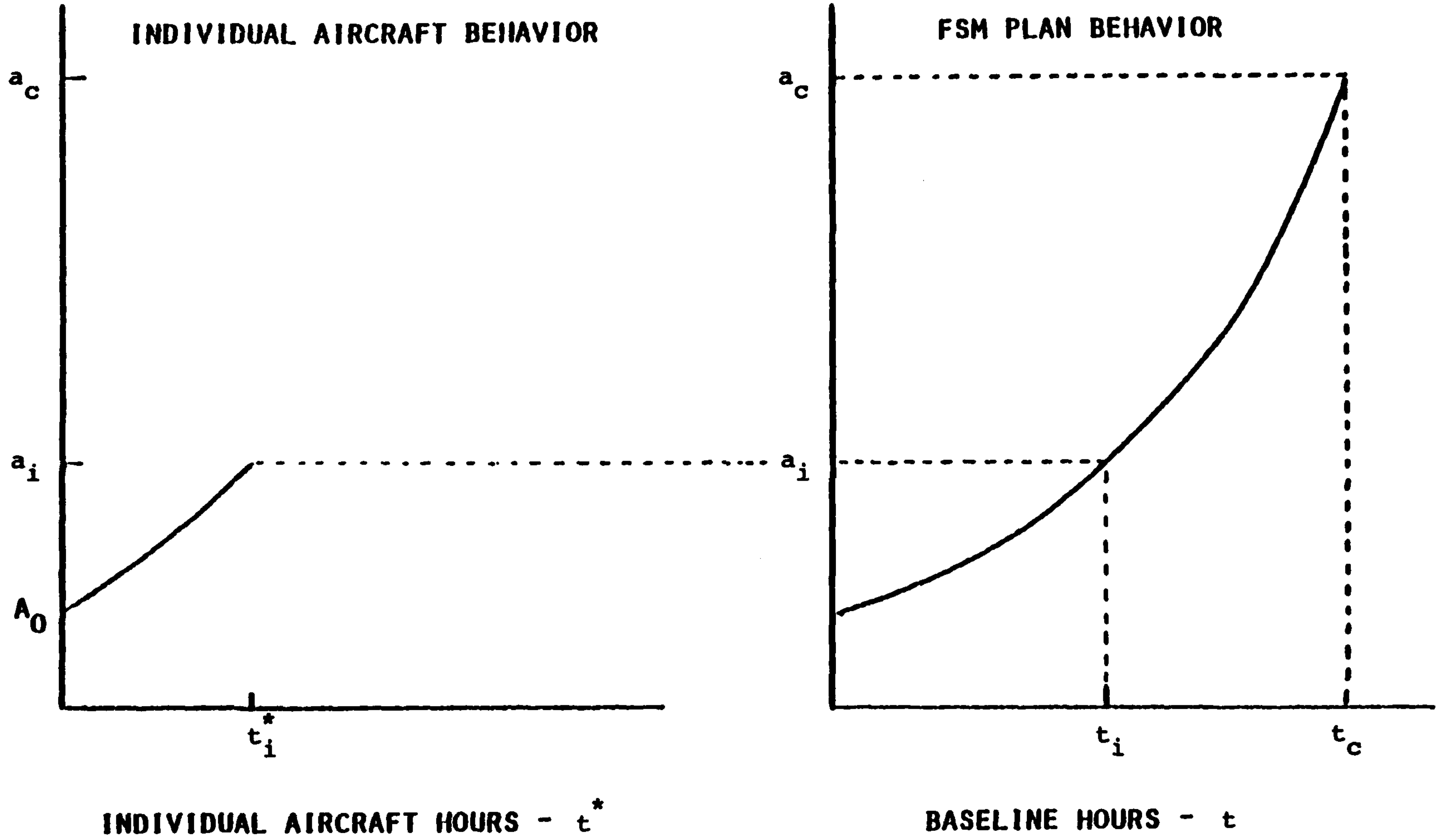


Figure 6. Correlating Individual Aircraft Usage to Baseline Usage.

Let

L_i = calendar time from date i to reach critical crack size.

R = conversion factor between aircraft flight hours (t^*) and baseline flight hours (t). $t^* = Rt$.

U = flying rate (flight hours/unit calendar time). $L = \frac{t^*}{U}$.

Then, at time i, the predicted calendar time until critical crack length is usually calculated as

$$L_i = \frac{(t_c - t_i)R}{U} \tag{1}$$

In any application, the individual terms of equation (1) will not be constant. In the following analyses, these terms are considered as random variables over the population of individual aircraft within a single stratification (as defined by base) of the fleet. In the examples to be presented, the IAT data from a recent (3rd quarter, 1979) IAT report on an attack/fighter/trainer aircraft (Reference 5) provided samples of distributions of the relevant variables. These distribution will be introduced and described as the need arises.

3.2.2 Error Analysis Of Time To Critical Crack Length

The actual calendar time required for a specific crack to grow to critical size can never be predicted exactly. Flying rates per month and the stress environment to be encountered will never correlate exactly with those used to predict the time to critical crack size. This analysis is directed to a measure of the possible "errors" that can result in the prediction of remaining calendar life by accounting for the random variation of the terms of equation (1).

Assume that each term of equation (1) is a random variable and that terms are statistically independent. A standard error analysis equation yields an estimate of the variance of remaining life (in calendar time) to be

$$\sigma_{L_i}^2 = \left(\frac{\partial L_i}{\partial R}\right)^2 \sigma_R^2 + \left(\frac{\partial L_i}{\partial U}\right)^2 \sigma_U^2 + \left(\frac{\partial L_i}{\partial t_c}\right)^2 \sigma_{t_c}^2 + \left(\frac{\partial L_i}{\partial t_i}\right)^2 \sigma_{t_i}^2$$

$$\approx \left[\frac{t_c - t_i}{U}\right]^2 \sigma_R^2 + \left[\frac{(t_c - t_i)R}{U^2}\right]^2 \sigma_U^2 + \left[\frac{R}{U}\right]^2 \sigma_{t_i}^2 + \left[\frac{R}{U}\right]^2 \sigma_{t_i} \qquad (2)$$

If the values of R, U, t_i, and t_c are taken to be mean values, then the coefficient of variation (ratio of standard deviation to the mean) of predicted time to critical size can be calculated from

$$\left[CV(L_i)\right]^2 = \frac{\sigma_{L_i}^2}{\bar{L}_i^2}$$

$$= \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_U}{U}\right)^2 + \left(\frac{\sigma_{t_c}}{t_c - t_i}\right)^2 + \left(\frac{\sigma_{t_i}}{t_c - t_i}\right)^2 \qquad (3)$$

In equations (2) and (3), σ_R, σ_U, σ_{t_i} and σ_{t_c} represent standard deviations of the appropriate random variables. σ_R measures the variability in the usage severity the individual aircraft will experience at the base. σ_U measures the variability in the number of flying hours the individual aircraft will be used over the period of projection. σ_{t_i} measures the variability in estimating baseline age due to the inability to calculate exactly the potential crack length of the individual aircraft, and σ_{t_c} measures the variability in the predicted life of the new structural detail in the assumed stress environment. Each of these will be discussed further in the following paragraphs along with example data.

3.2.2.1 Variability in t_c

The parameter t_c represents the time required for a crack of specified initial length to grow to critical in the baseline stress environment. The magnitude of this variability is difficult to specify as it must reflect not only the ability to predict time to grow a given crack to a critical size but must also account for material variation across the structural details in the fleet. However, in a recent round robin study performed by Committee E24.02.02 of ASTM it was concluded that ± 10 percent precision was the best that could be obtained for predictions of life in constant amplitude laboratory conditions. Thus, a coefficient of variation of 5-10 percent would represent the lower bound for variation in t_c. In the example error analyses which follow, σ_{t_c} will be assumed equal to zero. Assuming no variability in predicted life is a reasonable choice in interpreting tracking data since all structures are referenced to the same number.

3.2.2.2 Variability In Estimate of t_i

At time i, flight data from each individual aircraft is used to obtain an estimate, a_i, of the length of the potential crack at the critical location. Since the estimate is based on incomplete or imprecise data, a distribution of crack length estimates can be postulated to reflect the scatter in the estimate of the "true" crack length. This variability in crack length estimates transfers to variability in baseline hours as depicted in Figure 7.

Obviously, σ_{t_i} depends on the actual distribution of the estimates of a and on the function $a = f(t)$. For the purposes of the numerical examples the following assumptions will be made:

(1) $a = f(t) = a_0 e^{bt}$. This exponential fit for crack length as a function of time has been observed to provide a reasonable model for the shape of a crack growth curve in fighter aircraft (F-5A).

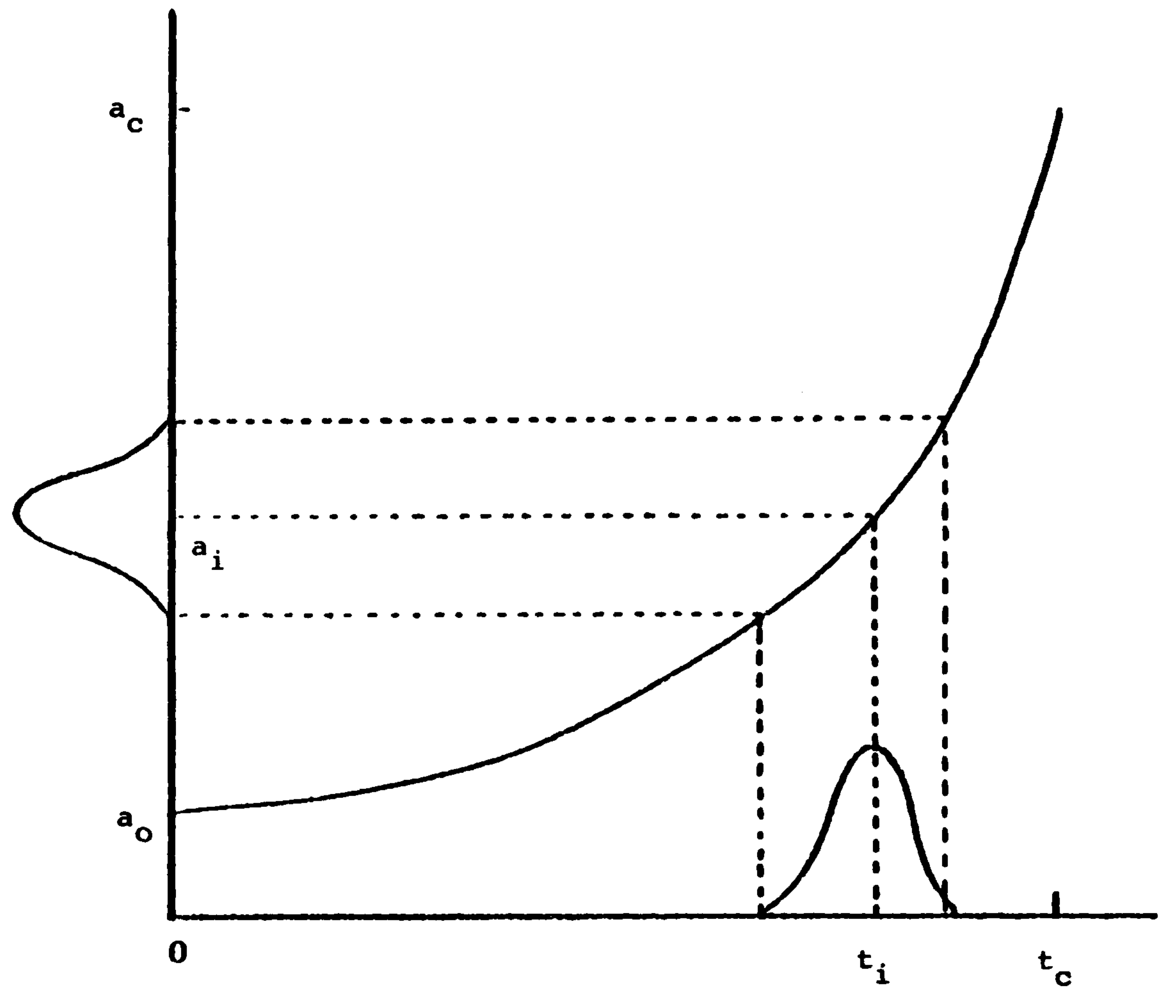


Figure 7. Conversion of Variability in Crack Length Estimate to Variability in Baseline Hours.

(2) $\sigma_{t_i} = f^{-1}(a_i + \sigma_a) - f^{-1}(a_i)$. This assumption implies that the transformation between a and t is approximately linear over the values of interest at the given point in time.

(3) the ratio σ_a/a_i is assumed to remain constant. It is reasonable to assume that the variance of the estimate will increase with flight time. This assumption specifies the rate of increase.

Under these assumptions

$$\sigma_{t_i} = \frac{1}{b}\left[\ln(a_i + \sigma_a) - \ln a_o\right] - \frac{1}{b}\left[\ln a_i - \ln a_o\right]$$
$$= \frac{1}{b} \ln\left(1 + \frac{\sigma a}{a_i}\right) \qquad (4)$$

Under the above assumptions, the constant coefficient of variation of crack length estimate (σ_a/a_i) leads to a constant standard deviation in the estimate of t_i.

In the numerical example, reasonable assumptions are $a_o = 0.050$ in. and $a_c = 0.25$ in. For this aircraft, $t_c = 4000$ baseline hours. Solving for b yields

$$b = \frac{1}{t_c} \ln(a_c/a_o)$$
$$= 4.024 \times 10^{-4}$$

Table 1 provides typical values of σ_{t_i} for selected choices of assumed coefficients of variation in the estimates of a_i. Note that for practical purposes in approximately symmetric distributions, a coefficient of variation of 0.1 implies that 60 to 75 percent of the estimates are within 10 percent of the "true" value. A similar interpretation can be applied to the standard deviations of baseline hours. For a CV = 0.1, 60 to 75 percent of the estimates of baseline age are within 236 baseline hours of the "true" value.

TABLE 1

VARIABILITY OF BASELINE AGES FOR SELECTED PRECISIONS IN ESTIMATE OF CRACK LENGTH AT IAT UPDATE

Coefficient of Variation in Estimate of Crack Length	Standard Deviation in Estimate of Baseline Hours (σ_{t_i})
0.05	121 hrs
0.10	236
0.15	347
0.20	453
0.30	652
0.40	836
0.50	1,008

3.2.2.3 Variability In Estimate Of Usage Rate (U)

When transforming from flight hours to calendar months it is customary to assume a constant usage rate per month, U, for all aircraft in the stratification of interest. It is recognized that individual aircraft will deviate significantly from U for any single month but it is assumed that over a long period of time, the deviations will average out. From the viewpoint of random errors in projected months to critical crack length, the variability due to different usage rates must be modeled and the model should reflect the fact that there is less relative variability in average usage over long time periods than there is over short periods. The following model is one approach to this problem.

Let U_j be a random variable which represents the flight time by a single aircraft in month j. The means and standard deviation of U_j are given by $\overline{U}$ and σ_U, respectively. Let U(m) represent the total flight time of the aircraft in the next m months,

$$U(m) = \sum_{j=1}^{m} U_j \tag{5}$$

Assuming that the U_j are independent, the mean and standard deviation of U(m) can be calculated as

$$\begin{aligned} \overline{U(m)} &= m\,\overline{U} \qquad \text{(hrs)} \\ \sigma_{U(m)} &= \sqrt{m}\,\sigma_U \qquad \text{(hrs)} \end{aligned} \tag{6}$$

Thus, when $\overline{U}$ is used in equation (1) to predict calendar months to critical crack length, the prediction is actually for the average number of months. The coefficient of variation for total

flight time in m months is given by

$$\frac{\sigma_{U(m)}}{\overline{U(m)}} = \frac{\sqrt{m}\ \sigma_U}{m\ \overline{U}} \tag{7}$$

$$= \frac{1}{\sqrt{m}}\ \frac{\sigma_U}{\overline{U}}$$

Thus, the coefficient of variation decreases as the number of months increases. It can also be noted that for m sufficiently large, the central limit theorem of probability indicates that the distribution of U(m) could be modeled by a normal distribution.

Recent A/F/T data (Reference 5) were used to estimate $\overline{U}$ and σ_U. Although the update listed cumulative flight hours at many time periods, there were many months for which no report was made. To circumvent this problem, cumulative flight times over a fixed 18 month period were obtained for each of 71 aircraft that were stationed at the base throughout the period The sample mean and standard deviation of these values of U(18) were calculated. Equation (6) was then used to calculate $\overline{U}$ and σ_U, the mean and standard deviation of flight hours per month. Figure 8 presents the observed histogram of the average flight hours per month obtained on the basis of averaging over 18 months. From these data

$$\frac{\overline{U(18)}}{18} = \overline{U} = 25.9 \text{ hrs.}$$

$$\frac{\sigma_{U(18)}}{\sqrt{18}} = \sigma_U = \frac{18\,(5.3)}{\sqrt{18}} = 22.5 \text{ hrs.}$$

The coefficient of variation of flight hours per month (not average flight hours per month) is

$$\frac{\sigma_U}{\overline{U}} = \frac{22.5}{25.9} = 0.87$$

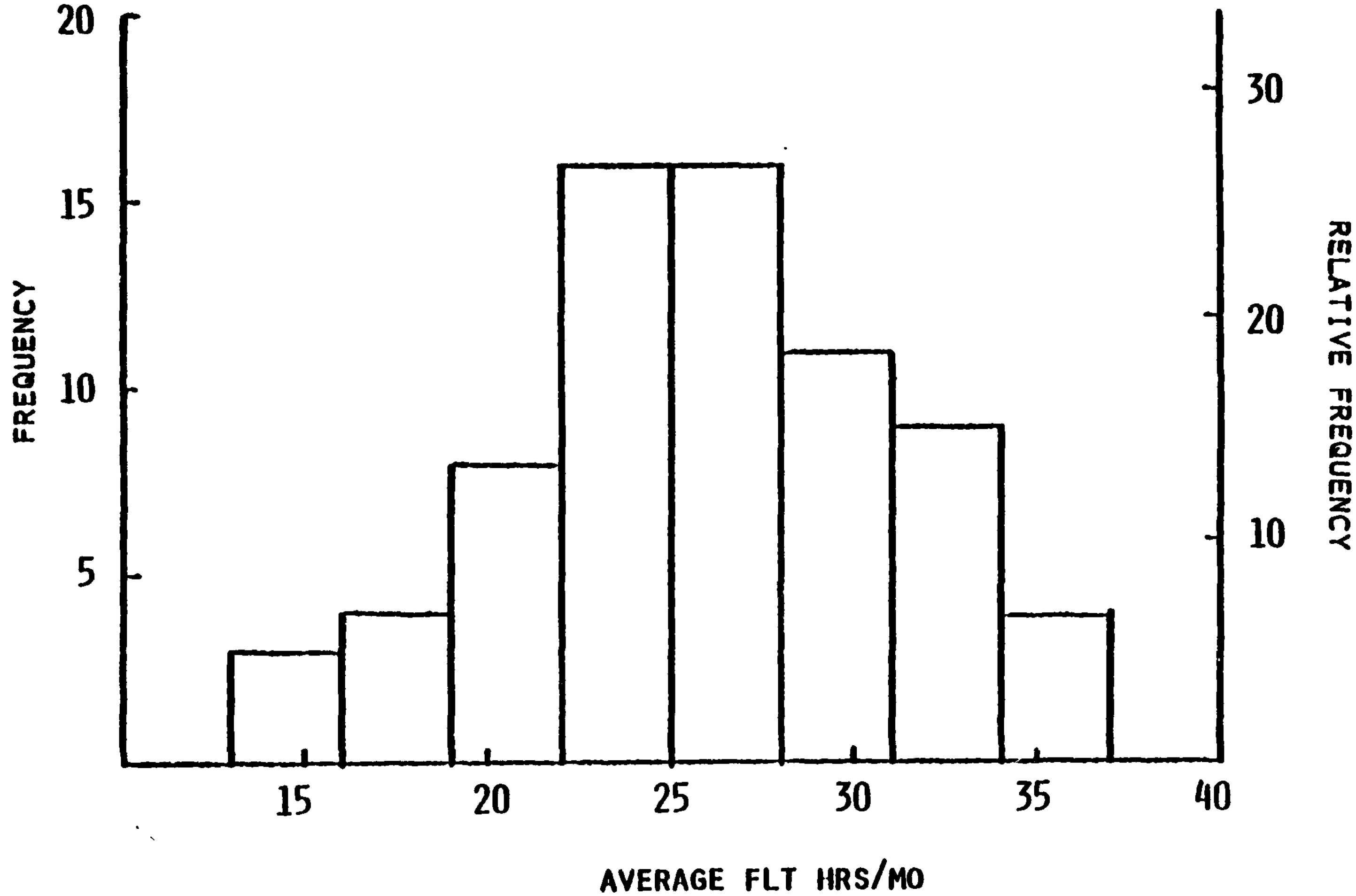


Figure 8. Histogram of Average Flight Hours Per Month Over a 18 Month Period.

To use this model of usage rate, equation (1) provides the estimate of the number of months until critical crack length based on average usage ($U = \bar{U}$). For this number of months, the standard deviation is calculated from equation (6) and again $\bar{U}$ is used to convert to months. Table 2 lists the standard deviations of the distributions of number of months to reach selected flight hours based on an average of 25.9 flight hours per month. Note in Table 2 that the standard deviation decreases in absolute value for shorter periods of projection but increases as a percentage of the mean. Therefore, projections over fewer flight hours exhibit a more significant variability.

It should be noted that a more exact model of months to achieve a fixed number of flight hours could be formulated. Let m be the random variable to be modeled under the constraint that

$$t = \sum_{j=1}^{m} U_j. \tag{8}$$

This far more complex approach could be developed, perhaps, along the lines of the work of Birnbaum and Saunders (Reference 6). However, the simple approach described above was judged to be sufficient for the purposes of this analysis.

3.2.2.4 Variability In Estimate Of Usage Severity Factor (R)

The usage severity factor, R, reflects differences in planned usage from the baseline usage that is expected to be encountered for particular subsets of the force. Individual aircraft within the stratification will experience different severity factors and, hence, a distribution of R values can be postulated. The severity factor employed for projections would be the average of this distribution ($\bar{R}$). While it may be possible to estimate the $\bar{R}$ value for the stratification from L/ESS type data, IAT data may also provide the necessary data to estimate $\bar{R}$. The method for achieving this estimate will depend on the

TABLE 2

EXAMPLE STANDARD DEVIATIONS OF MONTHS TO ACHIEVE SELECTED FLIGHT HOURS BASED ON AVERAGE OF 25.9 FLIGHT HOURS PER MONTH

Flight Hours (t)	Average Number of Months (T) to reach t Flight Hours	Standard Deviation of Months about the Projection T	Coefficient of Variation
4,000 (hrs)	154 (mo.)	10.8 (mo.)	0.07
3,000	116	9.3	0.08
2,000	77	7.6	0.10
1,000	38.6	5.4	0.14
500	19.3	3.8	0.20
250	9.7	2.7	0.28

output of the IAT. The method presented herein was derived from the data of the example A/F/T IAT output (Reference 5).

At each update of the IAT output, the flight hours and baseline hours are listed for each airplane by base. (Usage severity was stratified by base for this aircraft). The ratio of change in flight hours to change in baseline hours yields the R value (the random variable) for each airplane over the time period of interest. As in the usage rate description the period of time over which the changes are calculated will influence the variability of the computed R values about the average. In the example data of this analysis, averages and standard deviations were calculated from the flight and corresponding baseline hours over periods of the most recent 6, 12, and 18 months and the total time of each aircraft. These values are summarized in Table 3. Figure 9 presents the observed cumulative distribution functions of the R values from each of the four time increments. Note the decrease in variability as the averaging period increases. The σ_R^2 term of equation (2) is not constant but depends on the length of the projection (L_i). To account for this change in the error analysis, the observed values of Table 3 were linearly interpolated to obtain the standard deviations at predicted average calendar months to critical potential crack size.

3.2.2.5 Example Error Analysis Of Predicted Calendar Time to Critical Crack Length

Equation (2) provides an estimate of the variance (and standard deviation) of predicted calendar times for a potential crack to reach critical size. This standard deviation is a measure of the random error about the average predicted calendar time and reflects the possibility of errors due to mission severity (σ_R), usage rates (σ_U), and inaccuracies in estimate of current baseline age (σ_{t_i}). It is assumed that no bias is present in these distributions. This assumption implies that the U, R, and t_i are the average values of their respective distributions. Note that it is also assumed that t_c is determined without error ($\sigma_{t_c} = 0$).

TABLE 3

AVERAGES AND STANDARD DEVIATIONS OF
SEVERITY FACTORS FOR DIFFERENT TIME INCREMENTS

	$\bar{R}$	S_R
Last 6 mo.	1.94	1.01
Last 12 mo.	1.40	0.66
Last 18 mo.	1.21	0.33
Entire Aircraft Life	1.15	0.20

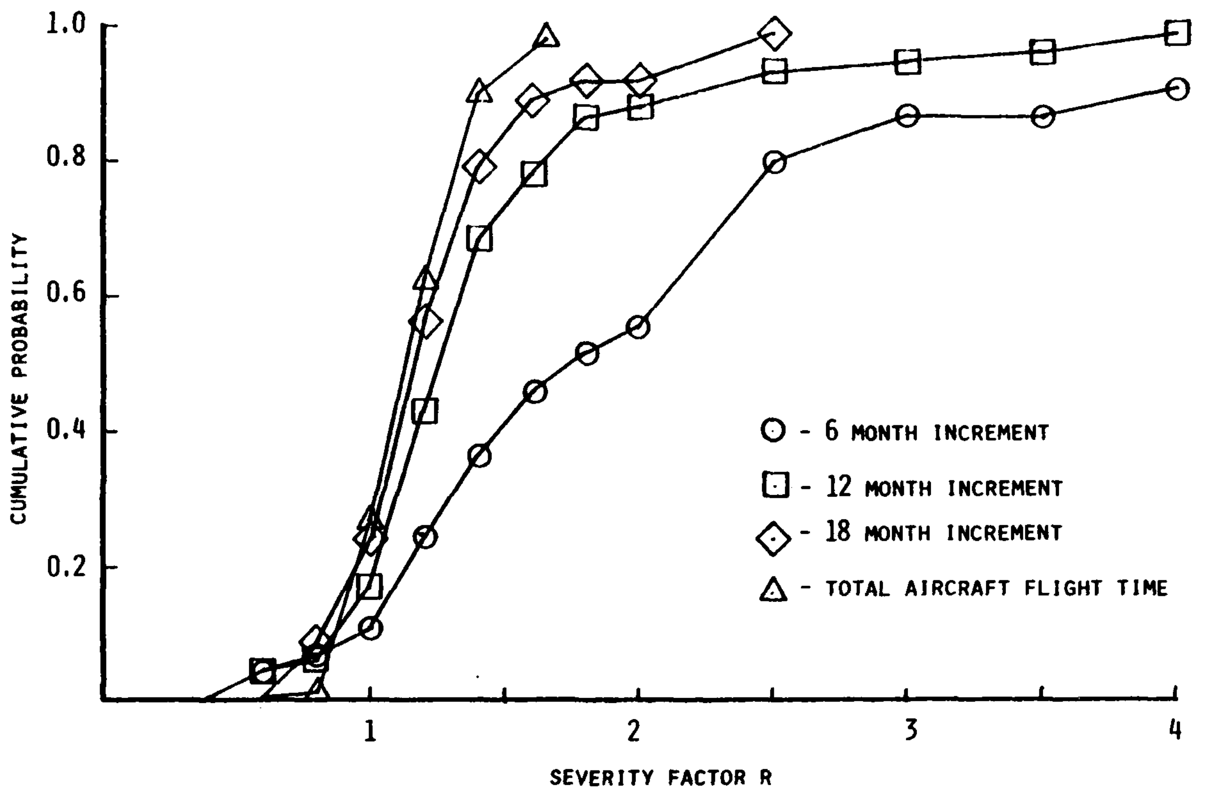


Figure 9. Cumulative Distribution of Severity Factors for Different Time Increments.

The IAT data discussed in the previous paragraphs were used in a parametric study of the standard deviations of prediction errors. In this analysis, it was assumed that t_c = 4,000 hrs, that the average severity factor for the future flights at this base would be $\bar{R}$ = 1.15 and that the average flying rate would be $\bar{U}$ = 25.9 hrs/month. Table 4 presents the standard deviations of prediction errors for selected baseline ages and selected coefficients of variation of potential crack length (converted to standard deviation of estimated baseline age). Also included in Table 4 are the predicted calendar times to critical crack length and the standard deviations of severity factors and usage rate for each calendar time projection period. Figure 10 presents the standard deviations of prediction errors as a function of predicted calendar months to critical potential crack length.

When the potential crack length is determined without error, $CV(a_i) = 0$, the resulting standard deviations of predictions are the result only of uncertainty in future usage. Over the range of data considered here, the future usage variability contributes to a standard deviation of 7 months when the projection time is about 1 year and about 18 months for projections over 5 year periods. The variability due to the potential crack length (baseline age) has a significant effect over the shorter projection periods as would be expected.

Since future usage is somewhat controllable, it is of interest to investigate the error projections assuming that flying rates and the severity factor are known exactly. Table 5 displays the standard deviations of times to potential critical crack lengths for no flying rate variability ($\sigma_u = 0$) and no severity factor variability ($\sigma_R = 0$) for selected baseline ages. For the projections of about 1 year, this data indicates that the primary variability is due to the variability in severity as opposed to variability in flying rates. The bottom line of Table 5 yields standard deviations of errors due only to the variation in the calculation of potential crack length. These

TABLE 4

STANDARD DEVIATIONS OF PREDICTION ERRORS OF CALENDAR TIME TO CRITICAL CRACK LENGTH NO ERROR IN ESTIMATE OF t_c

Remaining Life $t_c^* - t_i^*$ (hrs.)	L_i (mo.)	σ_R	σ_u	Baseline Age Standard Deviations						
				$CV(a_i)$ 0	0.05	0.10	0.15	0.20	0.25	0.5
				$\sigma_{t_i^*}$ 0	121	236	347	453	554	1008
4,000	176	0.15	11.5	82.2	82.4	82.9	83.6	84.6	85.8	93.6
3,500	155	0.15	10.8	67.9	68.1	68.7	69.6	70.8	72.2	81.3
3,000	133	0.15	10.0	54.3	54.6	55.3	56.4	57.9	59.6	70.4
2,500	111	0.16	9.2	42.3	42.7	43.6	45.1	46.9	49.0	61.2
2,000	89	0.19	8.2	31.7	32.2	33.4	35.3	37.6	40.1	54.9
1,500	67	0.20	7.1	21.6	22.3	24.0	26.5	29.5	32.8	49.7
1,000	44	0.26	5.8	14.1	15.1	17.6	20.9	24.6	28.4	46.9
500	22	0.32	4.1	7.1	8.9	12.7	17.0	21.3	25.6	45.3
250	11	0.71	2.9	7.0	8.8	12.6	16.9	21.3	25.6	45.3

t_c = 4,000 hours

U = 25.9 hrs/month

R = 1.15 (22.5 baseline hrs/month)

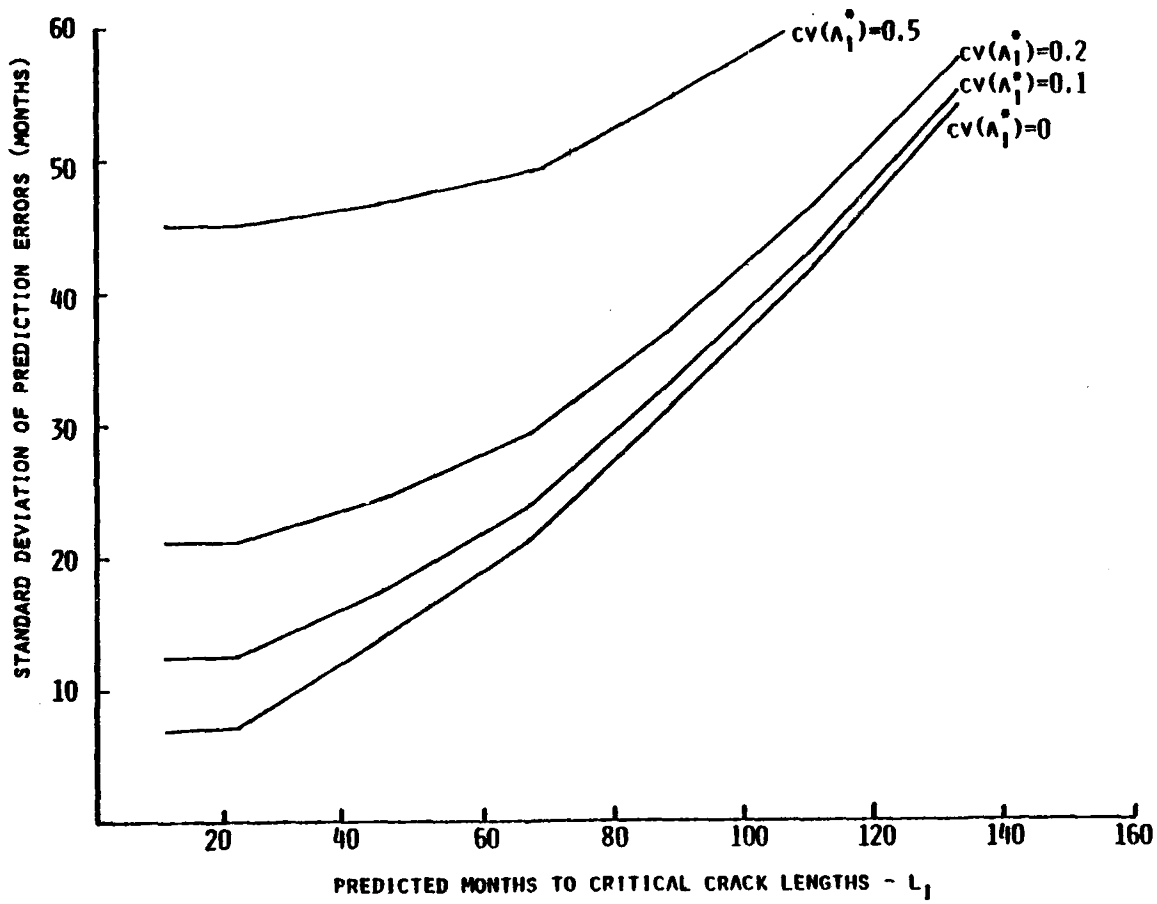


Figure 10. Standard Deviation of Prediction Errors as a Function of Predicted Months to Critical Crack Size - No Error in Estimate of t_c.

TABLE 5

STANDARD DEVIATIONS OF PREDICTION ERRORS
WITH NO ERRORS IN PREDICTED USAGE

Remaining Life $t_c - t_i$ (hrs.)	L_i (mo.)	σ_R	σ_u	Baseline Age Standard Deviations							
				$CV(a_i)$	0	0.05	0.10	0.15	0.20	0.25	0.5
				$\sigma_{t_i^*}$	0	121	236	347	453	554	1008
1,500	67	0.20	0		11.6	12.8	15.6	19.3	23.2	27.2	46.2
1,000	44	0.26	0		10.0	11.4	14.5	18.4	22.5	26.6	45.9
500	22	0.32	0		6.2	8.2	12.2	16.6	21.0	25.4	45.2
250	11	0.71	0		6.9	8.7	12.5	16.9	21.2	25.5	45.3
1,500	67	0	7.1		18.3	19.0	21.1	23.9	27.2	30.6	48.3
1,000	44	0	5.8		9.9	11.3	14.4	18.3	22.4	26.5	45.8
500	22	0	4.1		3.5	6.4	11.1	15.8	20.4	24.8	44.9
250	11	0	2.9		1.2	5.5	10.6	15.5	20.2	24.6	44.8
ALL		0	0		0	5.4	10.5	15.4	20.1	24.6	44.8

standard deviations are independent of baseline age due to the assumptions used in converting from potential crack length to baseline age and the exactness of the calculation of calendar months from remaining baseline hours to reach critical potential crack length.

To place these standard deviations of prediction errors in perspective, Figure 11 displays the cumulative distribution of calendar months to potential critical crack size for the aircraft at the base from which the usage distributions were obtained. For this stratification of this fleet, the total range of predicted months to critical crack length is 80 months. For the current ages, the standard deviations about these predictions range from 22 to 58 months for $CV(a_i) = 0.1$. Obviously, as the current age of a particular aircraft approaches the 4,000 hours design life the standard deviation will decrease. However, the minimum standard deviation for $CV(a_i) = 0.1$ is about 10 months (Table 5).

The above error analysis demonstrates that the acutal calendar time for a potential crack to reach critical for a specific airplane could differ significantly from predicted. The error would depend on the cumulative inaccuracies of the tracking system and the future deviations of the airplane's usage severity and operations from average. Before deciding on a level of acceptable error for a given aircraft and its set of maintenance actions, it is necessary to define the risk associated with not accomplishing the action at scheduled times. Realistic accuracy goals for recording usage or operations or improving the crack length predictions in a tracking system can only be set with an understanding of their individual and collective influences on the error in maintenance scheduling and associated risks.

It should also be noted that although the variations in flying rate and usage severity were obtained for only one aircraft type, it is felt that they are typical of the values to be encountered in the A/F/T aircraft class. The error sources will be present in all tracking systems and their magnitude will depend on the operational environment and FSM plans for the given force.

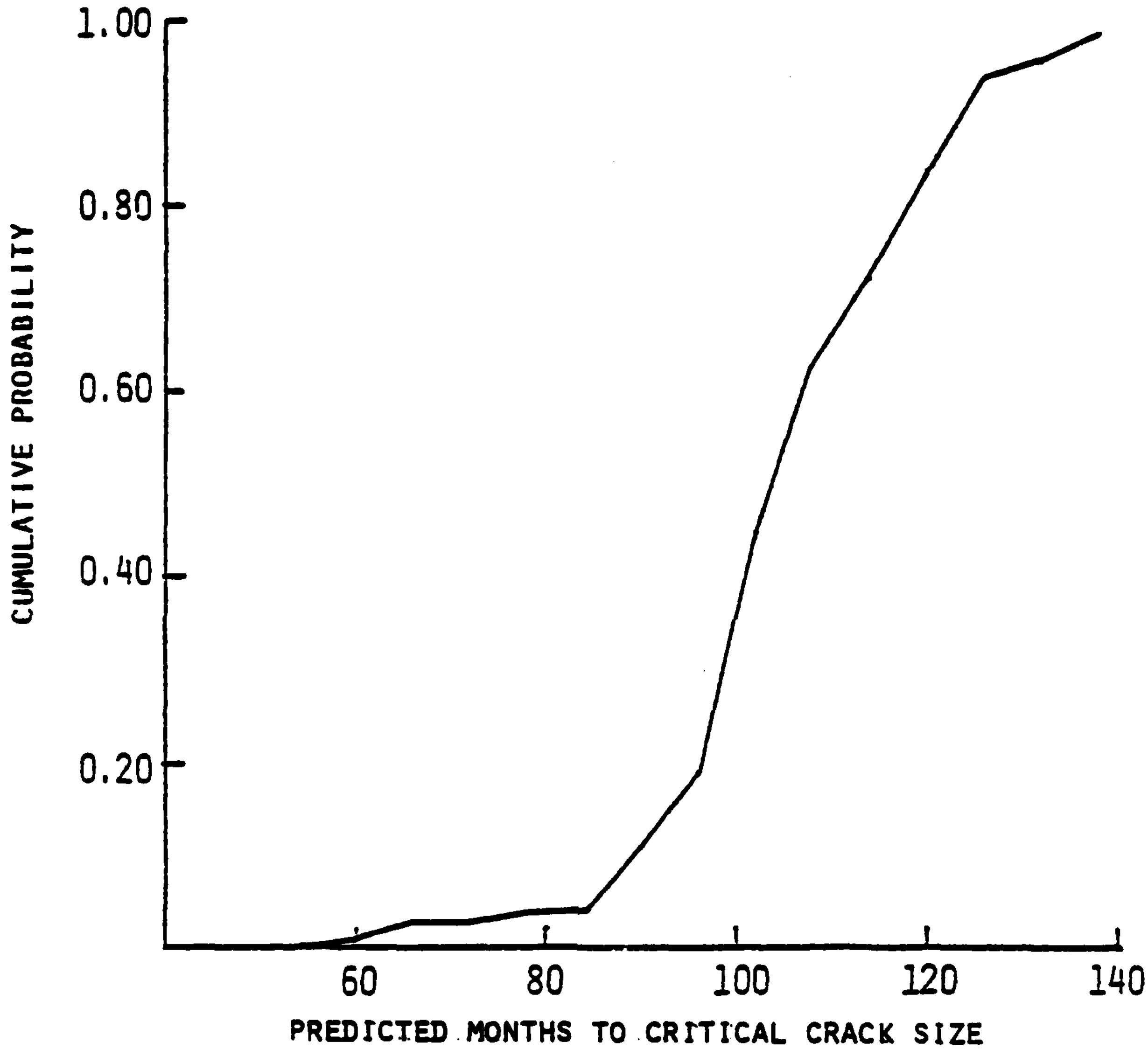


Figure 11. Cumulative Distribution of Predicted Months to Critical Crack Size for Aircraft at Base.

3.3 ACCURACY COMPARISONS AMONG TRACKING SYSTEMS

The preceding analysis provides a measure of the effects of the inaccuracy of tracking systems if the inaccuracy can be expressed in terms of a standard deviation of potential crack length at a critical point. However, it is a formidable problem to obtain this quantitative characterization from available data. The following paragraphs present a discussion of "accuracy" for current and potential methods of achieving the tracking function (Reference 1 and Volumes 2 and 3 of this report). Whenever possible, error magnitudes are quantified with the required accompanying assumptions.

The tracking systems are categorized jointly in terms of primary data source, analysis method, and recording device. The primary data sources considered are forms, stress measurements, counting accelerometers, and crack growth gages. Analysis methods and recording methods are considered within each of the sources.

3.3.1 Forms

The use of aircraft records and pilot logs as the primary data for individual aircraft tracking will continue in the forseeable future for transport/bomber aircraft, for those aircraft whose operational usage is homogeneous and known across the airplanes in a force, and as the most likely source of data for gap-filling when other tracking devices have failed. Forms data will be considered to be either of a general nature (aircraft records) or a detailed nature (pilot logs).

3.3.1.1 Aircraft Records/Gap-Filling

Every airplane in the Air Force inventory has a record which contains, as a minimum, the total number of landings and the flight time of the airframe and/or its major components. This data base is independent of the ASIP program but can be tapped if desired to achieve ASIP functions. In the past these records (in particular, the flight hours) have been a primary data source for scheduling maintenance actions. Future application will require the correlation between flight hours and crack growth since structural maintenance actions are to be scheduled on the basis of potential crack lengths at critical points. This approach to the IAT function is defined as Method 1 in Reference 1.

It is also important to note that while IAT is usually considered to consist of monitoring potential crack lengths at critical locations of each airplane, the estimate of time required for the potential crack to reach a given size is a desired output by the ASIP OPR. This projection is based on a predicted future usage and the correlation of other usage with potential crack length. Since this is the same correlation that would be used in an aircraft record tracking program, it can be seen that the projection of time to maintenance actions is the inverse of general forms monitoring and, hence, is present in all ASIP programs.

As a general IAT system, airplane records will have limited use. In fact, the lack of an acceptably strong correlation between flight hours and crack length has necessitated the IAT concept. However, there are two applications for an airplane records tracking program:

a) when all airplanes in a force will be subjected to approximately the same operational environment over a reasonably long time period, and,

b) when another data system has failed and gap-filling is required.

The first application will have limited uses in future systems. However, there are aircraft (e.g., the T-37 force) for which it has been determined that flight hour tracking provides sufficient accuracy.

Flight time from aircraft records will continue to play a significant role in the IAT function through its use in gap-filling as the secondary data source for almost all IAT programs. Missing or inadequate tracking data occurs in all tracking programs to some extent. Flight time from other sources provides a measure of the amount of missing data and the effect of the usage during the missing periods must be accounted for. This is usually accomplished through the correlation of flight hours with crack growth assuming an average usage over the appropriate stratification of force operation.

A general model for flight records monitoring can be formulated as follows. Assume that the potential crack can be adequately modeled by a crack growth rate model of the form

$$\frac{da}{dn} = g(a) \cdot f_1(\sigma) \tag{9}$$

where g(a) depends on crack length, crack geometry, and crack growth rate parameters of the structure. $f_1(\sigma)$ is a defined function of the number and magnitude of the stress cycles and is independent of a. (The Walker model is one example of a crack growth rate model which can be expressed in this form.) Neglecting changes in crack length during a flight, the incremental potential crack growth during the ith flight can be expressed as

$$\Delta a_i = g(a_{i-1})X_i \tag{10}$$

where a_{i-1} is the crack length at the beginning of the ith flight and

$$X_i = \sum_{j=1}^{N_i} f_1(\sigma_j) \tag{11}$$

is a usage random variable which summarizes the N_i stress cycles of flight i. After t flights, potential crack length is given by

$$a_t = a_o + \sum_{i=1}^{t} g(a_{i-1})X_i \tag{12}$$

In a flight records monitoring program or gap-filling procedure, no data is available to estimate X_i. Thus, a single value, μ_x, is derived which is representative of the "average" flight for the stratification of interest as defined during the L/ESS and DADTA. Potential crack length after t flights is estimated by

$$\bar{a}_t = a_o + \mu_x \sum_{i=1}^{t} g(a_{i-1}) \tag{13}$$

This model can be used both for tracking and gap-filling. However, in practice the predicted crack length as a function of expected usage time curve, f(t), would be used to estimate current potential crack length or a crack increment to be gap-filled for a periodic IAT update. The later can be estimated from

$$\overline{\Delta a} = \Delta t \; f'(t_1) \tag{14}$$

where Δt represents the increment of time to be gap-filled during the period and t_1 is the mid-point of the baseline life interval under consideration.

Equations (12 and 13) indicate that the major sources of error in flight record monitoring are:

(a) inaccuracies in the description of the average crack growth per flight by crack length function for the stratification of interest, and

(b) variability of individual airplane experience from the average over the time period of interest.

The error which results from inadequately defined average usage results from the sampling error of the L/ESS or from a change in operational usage from that determined during the L/ESS and updated DADTA. The questions of sampling error as a function of number of monitored flights and detection of usage changes are addressed in Section 4. The key consideration is that a given sample of data will provide average usage within known bounds (which depend on sample size), but it is not known in which direction the observed average differs from the true. Further, once an observed average is adopted, errors due to this difference are now propagated as an undeterminable bias, not as a random error whose average effect can be expected to get smaller over time.

Errors due to the variability of individual aircraft usage will depend on the particular aircraft type under consideration. No experience is available with the usage random variable, X_i, of equation (10) but past studies with Miner's damage indicate that the coefficient of variation of Miners damage per flight can be as large as 2 for bomber/transport aircraft and as large as 3 for attack/fighter/trainer aircraft (See Paragraph 4.2).

The IAT data from the attack/fighter/trainer aircraft (Reference 5) were analyzed as an example in quantifying the random errors associated with flight-by-flight variability. Again only data from one base were used. For this aircraft, tracking is performed through the calculation of baseline hours or damage index as a function of number of load factor exceedances. Assume that the calculated baseline hours provide an "accurate" measure of potential crack length (e.g. through the correlation shown in Figure 6). Then, deviations between baseline hours predicted from flight hours and baseline hours calculated from the load factor exceedances provide a measure of the flight time tracking error.

Figure 12 presents a scatter plot of baseline hours vs lifetime flight hours for the 86 airplanes at one base. The straight line is the least squares fit and deviations from the line represent the errors that would result from a prediction of baseline hours from flight hours. The standard deviation of the errors is 268 baseline hours. Since this standard deviation would be expected to increase with flight time, similar analyses were performed on data representative of periods of 6, 12, and 18 months. The results are summarized in Table 6. The standard deviations are increasing at approximately the rate of the square root of flight time which is a rate quite common to distributions of sums of random variables. Projecting backward at this rate indicates the standard deviation of baseline hours for one hour of flight time to be approximately 5-6 hours.

To transform these errors in baseline hours to errors in estimated potential crack length, the exponential crack length as a function of time model of Paragraph 3.2.2.2 was assumed. Figure 13 displays this relationship along with the predicted baseline hours at the 1840 hour average flight time and one standard deviation on either side of the prediction. Back calculation indicates that a standard deviation of 268 hours at the predicted 1640 hour baseline life is equivalent to a standard deviation of approximately 0.01 in. in potential crack length at a mean of about 0.10 in. (or a coefficient of variation of 0.10).

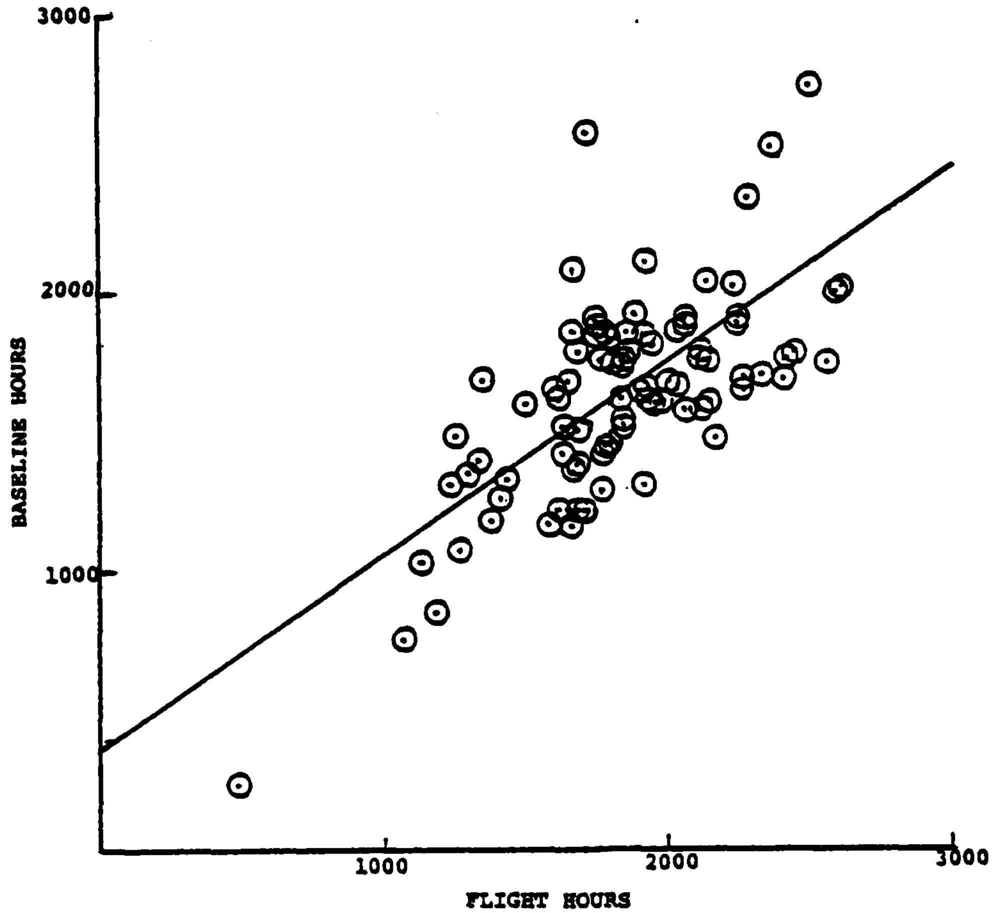


Figure 12. Flight Hours Vs Baseline Hours For A/F/T Aircraft At One Base.

TABLE 6

STANDARD DEVIATIONS OF BASELINE HOUR
ESTIMATE FOR 4 TIME PERIODS OF AN A/F/T AIRCRAFT

Time Period (Months)	Average Flight Hours Per Airplane In Period	Standard Deviation of Prediction Errors (Hours)
6	163	67
12	294	100
18	461	123
Current Lifetime	1840	268

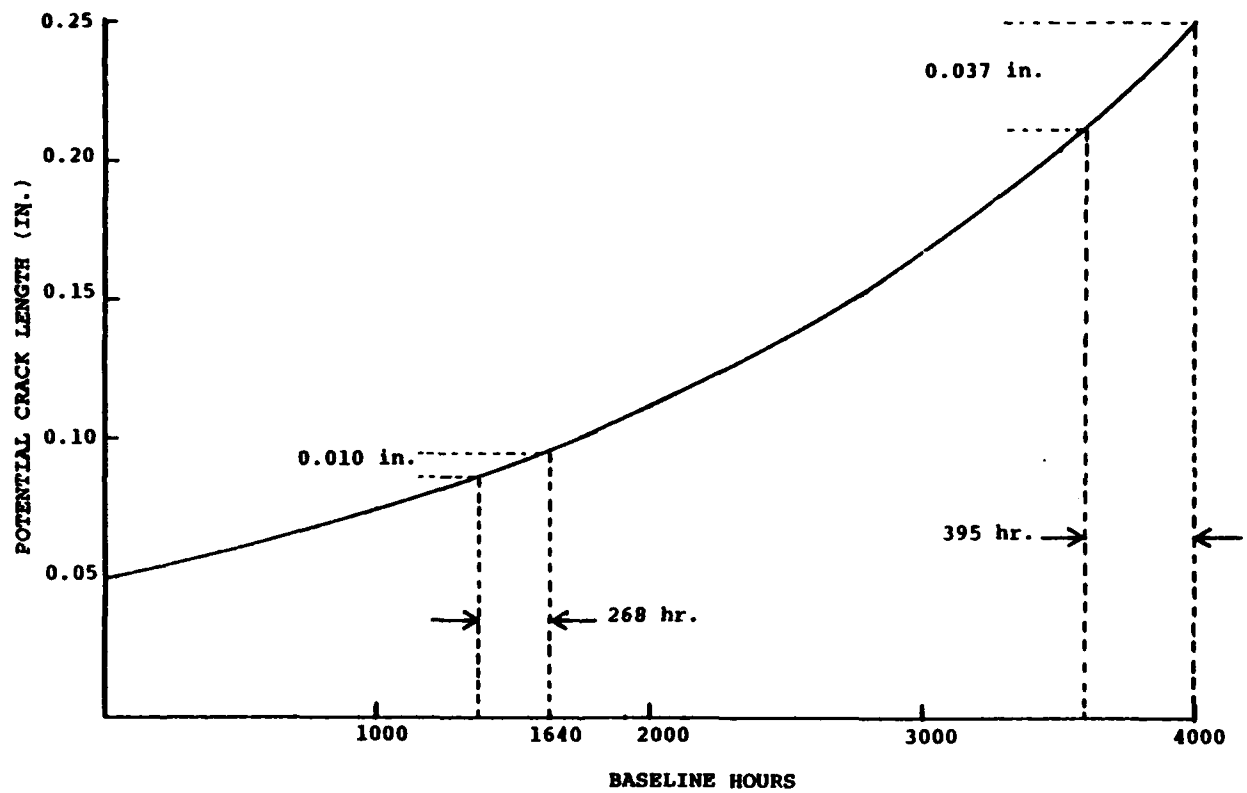


Figure 13. Estimation Of Potential Crack Length Error From Baseline Error.

If the error standard deviation continues to increase at the rate of $\sqrt{t}$, at a 4,000 hour baseline life, the standard deviation would be approximately 395 hour. The corresponding standard deviation of potential crack length would be 0.037 in. (or a coefficient of variation of 0.15).

Figure 14 presents a plot of flight hours versus baseline hours (calculated from pilot logs) for a recent IAT report of a transport/bomber aircraft. For this aircraft, the correlation is not nearly as strong as that of the A/F/T aircraft of Figure 12. These data display a standard deviation of prediction error of 910 baseline hours. Assuming this standard deviation increases as the square root of flight time, a backward projection indicates a standard deviation of 14 baseline hours for one hour of flight time. A crack length versus baseline hour curve was not available for converting this magnitude of error to crack length.

When flight hours are used for gap-filling, the standard deviation of the potential crack length errors due to the missing primary data depends on both the amount of missing data and when in the aircraft life it occurred. Under the assumptions of the preceding A/F/T example, the largest errors in potential crack length result at the end of a time period of interest. Assigning all the error at this point in time provides an overestimate of the error standard deviation. For example, if 10 percent of the primary data was missing at 4000 hours in the preceding example, the standard deviation of crack length error due to the gap-filled time is calculated to be $\sqrt{400/294} \cdot 100 = 116$ baseline hours which converts to 0.011 in. (4.5 percent) at 4,000 baseline hours.

3.3.1.2 Pilot Logs

Pilots logs are the only currently accepted primary data source for tracking large transport/bomber aircraft. This position has resulted from a combination of five factors:

(a) damage to these large aircraft results primarily from turbulence and readily recordable mission usage;

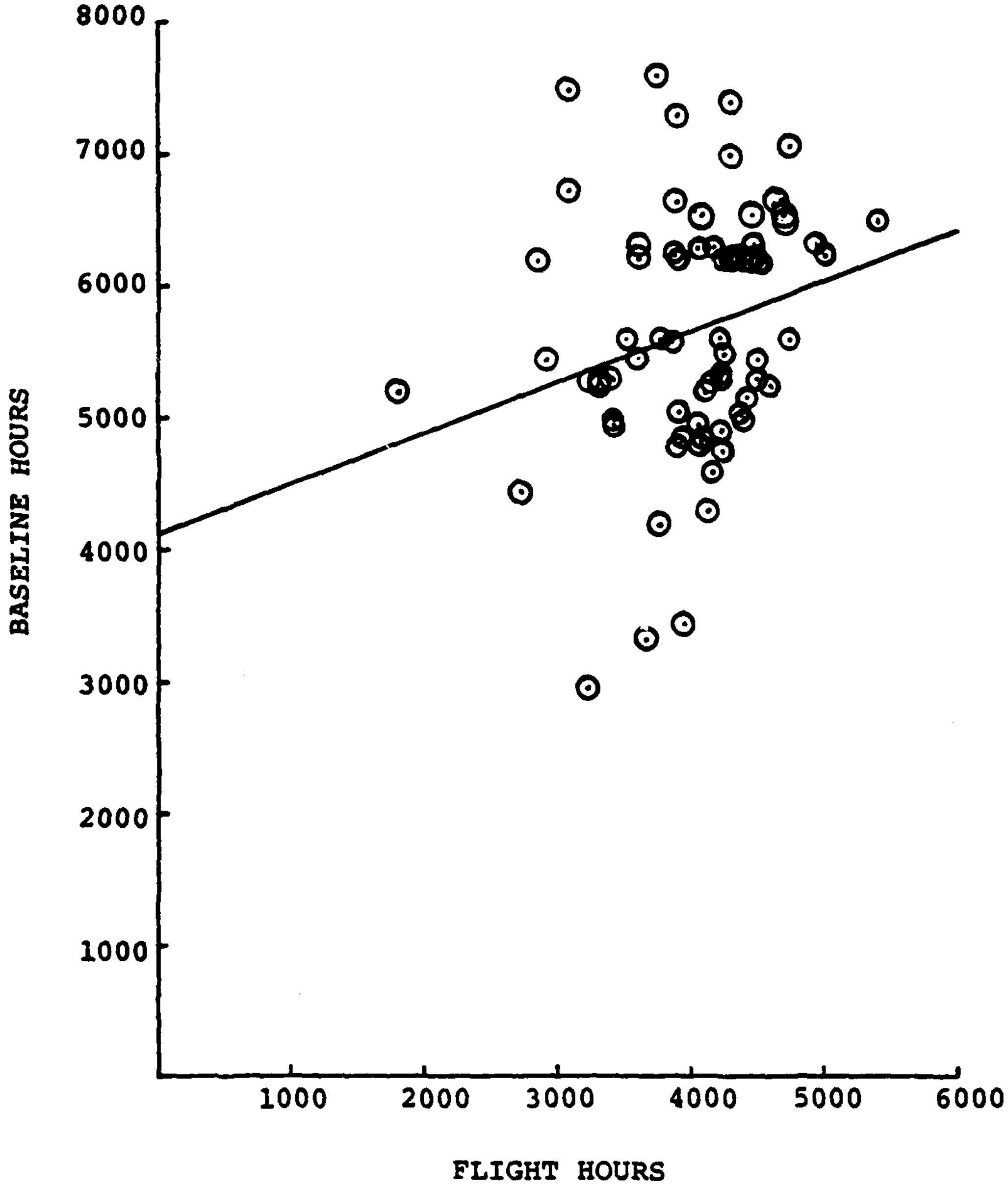


Figure 14. Flight Hours vs Baseline Hours For T/B Aircraft

(b) poor correlation exists between activity indicators at one location and stress magnitudes at another;

(c) an on-board crew member has available time for recording the necessary data;

(d) detailed knowledge of an individual aircraft's mission usage is commonly required to isolate causes of excessive potential crack growth; and,

(e) planned changes of mission usage are common and effects of such changes are readily evaluated in a pilot log tracking context.

Pilot log monitoring, as envisioned here, encompasses Methods 5 and 6 of Reference 1 and consists of modeling potential crack growth due to individual flights in terms of flight time or numbers of occurrences in combinations of weight, altitude, mach number and configuration (loosely defined). Potential crack growth is calculated for the flight conditions as defined by the stress conditions encountered during the L/ESS.

A model for the calculation of potential crack length in pilot log monitoring can be constructed as a generalization of equation (12). Let Δa_i denote the potential crack extension during the ith flight. Then, Δa_i can be modeled as

$$\Delta a_i = g(a_{i-1}) \sum_{j=1}^{q} T_{ij} R_j \qquad (15)$$

where T_{ij} represents the amount of time (or number of occurrences) of flight condition j during flight i and R_j represent a severity factor per unit which is representative of the flight condition. As an example calculation of R_j, assume crack growth is being modeled by the Walker equation

$$\frac{da}{dn} = C(1 - \alpha_R)^{m_1} (\beta(a)\sqrt{\pi a})^m \sigma_{max}{}^m \tag{16}$$

where C, m, m_1 = material dependent constants

$R = \sigma_{min}/\sigma_{max}$

α = constant which depends on R

$\beta(a)$ = *geometry factor.*

If flight condition j is characterized by p_j levels of stress cycles, then

$$R_j = \sum_{k=1}^{p_j} (1 - \alpha_{R_k})^{m_1} (\sigma_{max_k})^m N_{jk} \tag{17}$$

where

N_{jk} = number of $\sigma_{max\ k}$, $\sigma_{min\ k}$ cycles per unit time in flight condition j.

When N_{jk} is multiplied by T_{ij} in equation (15), the expected number of level j stress cycles during flight condition j of the ith flight is obtained.

The use of the model expressed in equation (15) is based on the premise that reasonbly accurate crack growth increments can be calculated from the average stress environments in each flight condition. For any particular flight on which a completed form is available, errors can result from three sources: (a) the sampling error in determining the average environments during the L/ESS; (b) the difference between the assumed stress environment and that actually encountered and, (c) errors in the recorded data on the pilot log. The first source of error cannot be measured but would decrease with quantity of data in the L/ESS. Further, the error would be propagated as a "bias" for any one flight condition but these "biases" could average out when all the flight conditions for a flight are combined.

The differences between the assumed and encountered stress environments in a flight condition introduce a random error into the calculation. To data, no data has been published which can be used to measure the magnitude of this random error and, hence, it is not possible to quantify the errors that could result in pilot log trackings. Care will be required in combining the errors from the different flight conditions. Since equation (15) displays that Δa_i is a weighted average of the potential crack growth during the flight conditions encountered, the variance of the errors in incremental crack growth during a flight will be a weighted average of the variances of the errors in each flight condition.

Errors which result from inaccurate data on the forms (after editing) are non-measurable and probably negligible. Adequate crew training is assumed to assure a conscientious attempt to accurately complete the log. Recording errors which occur can then be assumed to be relatively infrequent, randomly distributed, and inconsequential.

The fourth source of inaccuracies in pilot log tracking results from gap-filling based on aircraft logs. The percent of missing data on current pilot log programs ranges from 0 to 30 percent (Reference 1). In view of the weak correlation between flight hours and baseline hours that can be present in transport/bomber aircraft (as displayed in Figure 14), this source of error could be quite significant if there is a high percentage of missing data.

Considering the error sources in pilot log tracking, their ranking in decreasing order of importance would be: inaccurate average usage for flight conditions; variability of individual excursions from average conditions; missing data; and inaccurate recordings on form.

3.3.2 Strain Measurements

For most critical locations in attack/fighter/trainer (A/F/T) aircraft, the damaging stress cycles result primarily from pilot induced maneuvers. Since there is a high degree of variability in the stresses produced in performing a particular maneuver, and, since individual A/F/T aircraft of a force are not typically subjected to the same maneuver environment, tracking will generally be accomplished in these aircraft through an activity indicator which is dependent on the severity of individual maneuvers. The strain histories at control points provide a obvious choice of tracking data. Accuracy resulting from the use of strain measurements will be considered from the viewpoints of cycle-by-cycle and parametric analyses.

3.3.2.1 Cycle-By-Cycle Analyses

Due to the definition of accuracy postulated in Paragrash 3.1, a strain history at a critical point has the potential of providing the most accurate tracking system. A strain history can be reduced to a sequence of stress peaks and valleys and this input would be sufficient for any crack growth model in the forseeable future. However, in the practical application of a strain based, cycle-by-cycle tracking system, the ideal will not be achieved. There are three sources of errors that will be present in this tracking system:

a) stress transfer,

b) missing data,

c) inaccurate recording or reduction.

In a cycle-by-cycle analysis based system, it is possible that the analysis would be applied at a limited number of control points and potential crack growth at other critical locations would be inferred from the control. This correlation between control points and critical points is another source of error for the potential crack growth at the critical point but is considered a parametric analysis.

To quantify the magnitude of possible errors associated with stress transfer and inaccurate recording or reduction, consider the crack growth formulation of equations (9) through (12). In particular, incremented potential crack growth during the ith flight is expressed as

$$\Delta a_i \approx g(a_{i-1}) \sum_{j=1}^{N_i} f_1(\sigma_j) \tag{18}$$

Assume that the crack growth rate is reasonably modeled by the Paris equation

$$\frac{da}{dN} = c\ \Delta k^m \tag{19}$$

for which it can be shown that

$$f_1(\sigma) = (\Delta\sigma)^m \tag{20}$$

Then

$$\Delta a_i \approx g(a_{i-1}) \sum_{j=1}^{N_i} (\Delta\sigma_j)^m \tag{21}$$

where $g(a_{i-1})$ is independent of the stress history during a flight. Let $\Delta\sigma_j$ be the true change in stress during the cycle and $\Delta\hat{\sigma}_j$ be the estimate from the stress measurements. $\Delta\sigma_j$ can be modeled as

$$\Delta\sigma_j = \Delta\hat{\sigma}_j + \varepsilon_j \tag{22}$$

where ε_j is the random error component. It will be assumed that the stress measuring system is unbiased, $E(\varepsilon_j) = 0$, and that the standard deviation of the errors, $s(\varepsilon)$, is a constant proportion of the true value,

$$c = \frac{s(\varepsilon_j)}{\Delta\sigma_j} \tag{23}$$

for all j. As before, let

$$X_i = \sum_{j=1}^{N_i} (\Delta\sigma_j)^m$$

$$= \sum_{j=1}^{N_i} (\hat{\Delta}_j + \varepsilon_j)^m \tag{24}$$

But, in the tracking system X_i is estimated by

$$X_i = \sum_{j=1}^{N_i} (\Delta\hat{\sigma}_j)^m \tag{25}$$

For aluminum m is generally in the range $3 < m < 4$. Letting $m = 3$, expanding (24), and taking expected values over the population of measurement and transfer errors yields

$$E(X_i) = \sum_{j=1}^{N_i} \Delta\hat{\sigma}_j^{\,3} + 3 \sum_{j=1}^{N_i} \Delta\hat{\sigma}_j \left[s(\varepsilon_j)^{\,2} \right]$$

$$= \sum_{j=1}^{N_i} \Delta\hat{\sigma}_j^{\,3} + 3\, c^2 \sum_{j=1}^{N} \Delta\hat{\sigma}_j^{\,3} \tag{26}$$

$$= (1 + 3c^2) \sum_{j=1}^{N_i} \Delta\hat{\sigma}_j^{\,3}$$

$$= (1 + 3c^2)\hat{X}_i$$

For $m = 4$

$$E(X_i) \approx (1 + 6c^2)\hat{X}_i \tag{27}$$

Therefore, ignoring the random errors associated with measurement or stress transfer error results in a biased estimate of the potential crack growth during a flight. Further, the bias is unconservative in that it underestimates the potential crack change. This qualititive result holds for all $m > 1$.

The magnitude of the coefficient of variation, c, depends on the random variation associated with installation, material repeatability, and data reduction and processing errors as well as the errors associated with stress transfer. The former error sources are often combined in a blanket statement that measurement errors are within, say 5%. Using the 5% as a 3 standard deviation measure would imply that $c = 0.05/3 = 0.0167$. Note that using only this source of error will result in a 1 percent bias in the estimate of per flight crack growth if $m = 3$.

The errors due to stress transfer will depend on the particular structures and the length of the transfer. Figure 15 reproduces from Reference 7 a plot of simultaneous stress measurements from adjacent gages on lower wing skins during one flight of an F-5A aircraft. While recognizing that both stress measurements contain data recording and processing errors, if the observed linear correlation is used to predict one of the stresses from the other, a "random" error will result (the line in Figure 15 is the 45° line not a least squares fit.) In this particular example, the coefficient of variation would be on the order of 0.10 which would result in a 3 percent bias in the crack length increment of an average flight of $m = 3$ and a 6 percent bias if $m = 4$. With a very careful characterization of the stress measurement and stress transfer precisions, these biases could be removed. However, the particular stress errors actually encountered during each flight will contribute to a random error that will be present even after correcting for the bias or average error.

The magnitudes of the errors that result from missing data will depend on the amount of missing data and the gap-filling technique. A model for combining accuracies of the primary calculation and gap-filler as a function of percent

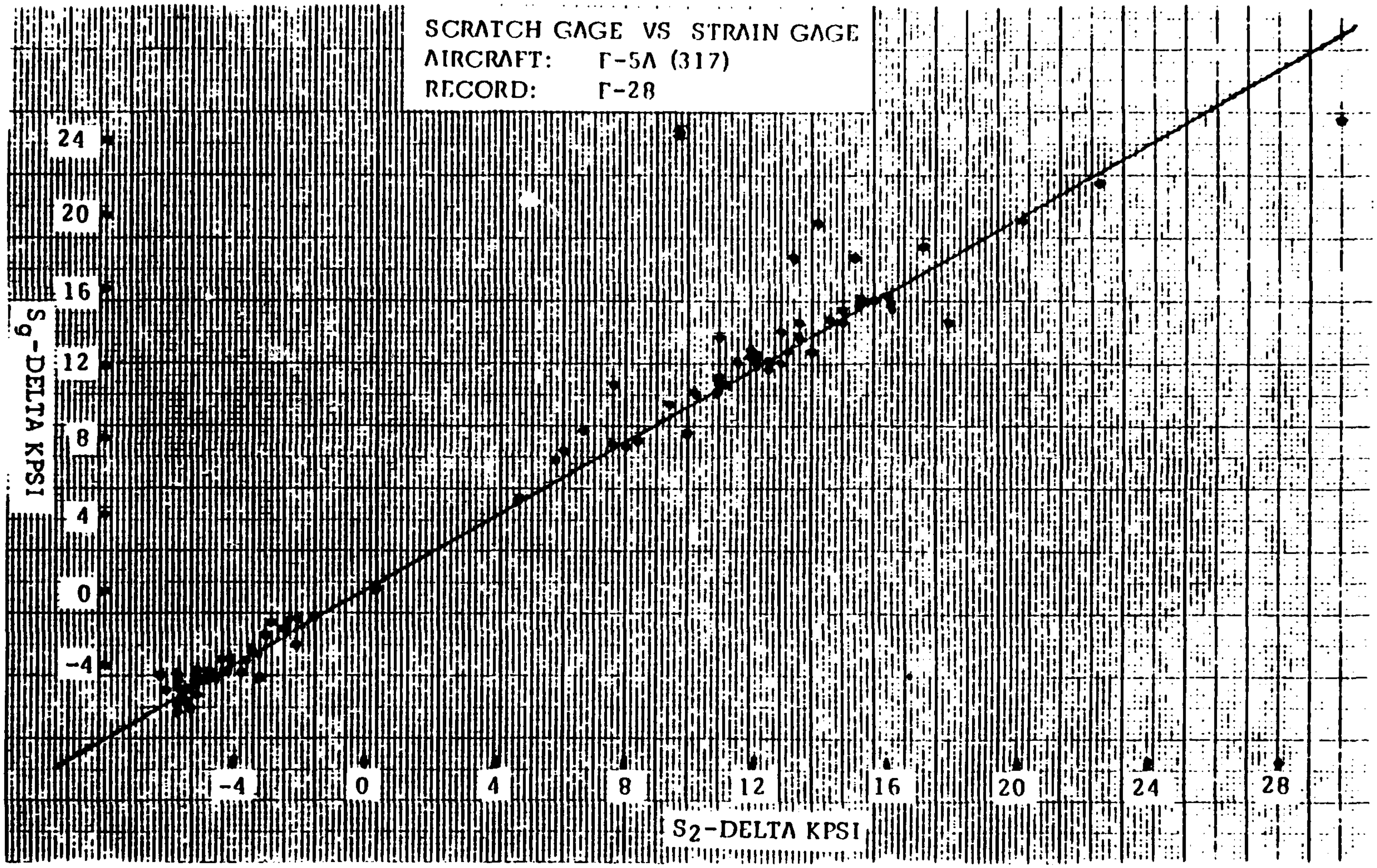


Figure 15. Correlation of Simultaneous Strain Peaks at Two Adjacent Locations.

of missing data has not yet been formulated. Thus, only subjective judgements regarding overall accuracy can be made when comparing computing tracking systems.

Tracking based on cycle-by-cycle crack growth can be accomplished by electronic or mechanical strain recorders. While electronic strain gages have not been employed as a primary data source for tracking, they have been used in L/ESS programs. In general, the reliability of the strain channels has been poor (Reference 1), requiring far too much gap-filling in a tracking application. The use of factory installed redundant gages increases reliability but requires decision making during data processing. Thus electronic strain measurements for tracking would only be practical given a microprocessor type recorder that could perform sophisticated edit functions.

While the concept of using mechanical strain recorders (MSR) as a primary data source for monitoring structural usage is not new, large scale field applications have been made only recently for the F-16, A-7, and F-5 aircraft. MSR data cassettes from the F-16 and A-7 programs are being automatically transcribed to digital format at the ASIMIS. Since these programs are relatively new, a review of their experience would be somewhat premature. However, in connection with the F-5A/B Service Life Extension Program, the San Antonio Air Logistics Center instrumented approximately 100 aircraft from six countries with MSR recorders. The data from these recorders were transcribed semi-automatically on an Aeronautical Systems Division optical reader and provide a strong indication of the experience that can be expected during field use of the MSR (See Reference 8).

The data were collected between mid-1978 and mid-1979. During the program, 373 cassettes were received which, according to accompanying data sheets, were representative of 14,995 hours. A summary of the recorded data by quarter of receipt is presented in Table 7. The table indicates the number

TABLE 7

SUMMARY OF MSR DATA PROCESSED

	QUARTERS					
	1	2	3	4	TOTAL	
Total Hours Received	2795	2464	1996	7700	14955	
Valid Data	1422	1217	1840	5690	10169	68%
Invalid Data						
Saturation	1220	1072	42	1153	3487	23%
No Reference Track	44	132	0	359	535	4%
Recorder Loose	0	0	0	310	310	2%
Data Sheet Missing	48	43	0	134	225	<2%
Trace too light to read	0	0	55	45	100	<1%
Normal Jumps 100 cts., resulting from a blow to the recorder	61	0	0	0	61	<1%
Loose Tape in Cassette	0	0	59	0	59	<1%
Flight Overlapping	0	0	0	9	9	<1%

of flight hours of data received in each quarter, the number of flight hours of valid data, and the number of hours of invalid data by cause. Over the 1 year period, 68% of the received data were valid. The major cause of invalid data was saturation of the recording cartridge (inefficient tape available for recordings). This cause is correctable by more frequent inspecting or changing of the cartridges. In fact, the last 2 quarters had significantly higher percentages of valid data than the first 2 quarters due to a change in the inspection frequency of the individual cassettes.

Causes of invalid data other than saturation and missing data sheets are less controllable and tend to reflect instrument reliability. The other causes resulted in a total data loss of about 7%. Without hardware modifications, the upper limit of valid data attainable would be approximately 93%. Therefore, when the MSR is used for the IAT function, some form of gap-filling will be required and, in the practical application, for approximately 10 percent of the flight time.

Although the data were transcribed by semi-automatic methods during this study, it is of interest to summarize the costs as upper bound costs that could be expected in MSR data reduction. First, the tasks performed by the data technicians included the following steps:

1) Log in and inspection of incoming tapes and forms;
2) Semi-automatic conversion of peaks and valleys to punched paper tape;
3) Produce card deck and listing from punched paper tapes;
4) Preliminary data edit and correction;
5) Computer edit which identified range-pair-range cycles;
6) Recheck of largest cycles on each cassette and make any required corrections to cards.

The cost of performing these operations including supervision (but no software preparation) was $16,400 in 1979 dollars (Reference 7). For the 10,169 valid hours this cost ccrresponds to $1.60 per hour. However, cost per hour may not be an appropriate base due to variations in usage. A total of approximately 200,500 peak-valley pairs were obtained from the 10,169 valid hours for a cost of $0.082 per stress cycle. The data were contained on 373 cassettes for a cost of $44 per cassette. It should be noted that these costs include start-up and learning phases and that some early inefficiency resulted from sporadic cassette arrivals from the field.

3.3.2.2 Parametric Analyses

Recorded measurements of stress can be used as accurately determined activity indicators from which estimated potential crack length is obtained parametrically. Stress sequences for each critical point are obtained as a baseline spectra (either design or updated on the basis of an L/ESS) and potential crack length as a function of baseline hours is obtained by analysis or test. Stress exceedances from the baseline spectra are summarized for the control point and this summary is correlated with the stress exceedances observed during a tracking period to determine incremental crack growth during the period. To date, two methods have been suggested for achieving the correlation: the normalized stress exceedance method (Method 11 of Reference 1) and a regression analysis method (equivalent to Method 10 of Reference 1).

In the normalized stress exceedance method, the severity of usage of the aircraft during the time period of interest is quantified by interpolating on the slope of the least squares fit to an observed exceedance curve between usage severities of known crack length vs baseline hours curves. Crack length in the time period is incremented accordingly. No analytical method is available for quantifying the errors associated with this process.

The regression analysis method is based on the development of a set of constants from which baseline hours for the individual aircraft are predicted from total flight hours and counts of level crossings of stress. The coefficients are obtained from a least squares fit (regression) of known baseline hours and counts of level crossings for various severities. This method has not yet been used in a tracking program so no data is available for any form of error analysis. However, this approach is completely analyogous to the regression approach using counting accelerometer readings as the primary data source and one error source is quantified in the discussion of this tracking method (Paragraph 3.4).

Given an estimate of equivalent baseline hours or damage index for a particular airplane, potential crack length at other critical points can be estimated by means of crack length curves (as in Figure 6). A somewhat equivalent method is through the use of normalized crack growth curves which require denormalization factors to convert to crack length or time. In either case, errors associated with the potential crack length estimates are not generally quantifiable. Note, however, that the stress environment of some critical points could be poorly correlated with the measured stresses. For such critical points, stresses at the remote location are no better activity indicators than, say, normal acceleration at the center of gravity.

3.3.3 Counting Accelerometers

Counting accelerometers have long been used as activity indicators for singling out aircraft that have been subjected to a greater than normal stress environment. The requirements of MIL-STD-1530A dictate that the measure of usage severity be expressed in terms of potential crack length. To date this has been accomplished from counting accelerometer data only by means of a parametric analysis in which baseline hours (or, equivalently, damage index) is computed as linear combination of exceedances of fixed n_z levels and flight time (Method 10 of Reference 1). As in the case of parametric crack growth analysis

from strain measurements, the coefficients are determined by correlation with the n_z spectra of the stress exceedances that have produced the crack length vs baseline hours curves. The resulting errors are not quantifiable but two potential sources can be considered.

Normal acceleration is fairly well correlated with wing stresses in A/F/T aircraft but other parameters must be included for a more accurate stress prediction. In deriving the relationship between n_z level crossings and crack growth, all other parameter are ignored under the assumption that their values are representative of force usage. If operational usage changes significantly, the correlation between n_z and crack growth could also change significantly and the correlating equations between n_z and crack growth would need to be modified. In particular, the next most important parameters for calculating stress would be the mission parameters of aircraft weight and configuration. To minimize this error source, the accelerometer counts could be recorded after each flight and submitted with mission data which describe weight and configuration. Although this approach has been used in tracking systems based on Miner's damage, no crack growth based system has been made operational using flight-by-flight accelerometer recordings. The added requirement of a form (accurately completed) for each flight could lead to a high percentage of missing data and, hence, more inaccuracy due to gap-filling. On the other hand, the constant recording of accelerometer counts could lead to quicker detection of counting accelerometer malfunctions. The effects of this trade-off are unknown in general. However, the A-7 IAT program is based on monthly readings of the counting accelerometers and reports a data capture rate of 70%. The A-10 IAT program requires flight-by-flight recordings and reports a capture rate of 90% (See Reference 1). The causes of the missing data would have to be investigated before a general conclusion regarding missing data from the two approaches could be formulated.

The second error source which can be addressed relates to the error which results from a regression equation for predicting damage index. From Volume 3 of this report, an equation for predicting damage index is given as

$$DI = 0.004 + 0.0000689E_5 + 0.000204E_6 + 0.0000717(\text{Time}) \qquad (28)$$

where E_5 and E_6 are cumulative exceedances of 5g and 6g, respectively, and Time is total airplane flight hours. For this aircraft,

$$\text{Baseline Hours} = 4000\ DI \qquad (29)$$

The equation was derived on the basis of a least squares fit for seven distinct usage severities. When the regression equation is applied to the initial data, the estimated coefficient of variation of the prediction errors is 4 percent. Note this error measure applies to the ability of the linear equation to model damage index. It does not include differences in potential crack length that would be due to variations in stress for a fixed n_z level and sequence effects of the stress spectrum. However, the 4 percent coefficient of variation does represent a lower bound on the variability in the predicted baseline hours for a particular airplane.

3.3.4 Crack Growth Gages

The crack growth gage is a generically different approach to tracking than those previously considered. The gage is a small, cracked structural element which is attached to the structure being monitored and which experiences the same stress environment of the control point. The length of the crack in the gage is the activity indicator and the tracking function is accomplished by correlating this actual gage crack length with potential crack lengths at critical location in the structure.

Several research problems need to be resolved before the crack growth gage can be considered as a practical tracking device. They include the demonstration that the correlation between gage and structural crack length can be made independent of the stress spectrum and the practical problems associated with field applications. However, a general observation regarding error variability can be made regardless of the resolution of these problems.

Since it is impossible to manufacture two absolutely identical gages with absolutely identical initial cracks, a population of crack growth gages subjected to identical stress environments would display a distribution of crack lengths at any point in time. Conceptually, the curve defined by the means of these distributions would be the accurate potential crack length indicator by analogy with the definition of accuracy of Paragraph 3.1. Since the behavior of a randomly selected gage from the population will not be known in advance, deviations from the average curve can be considered as random errors.

To present an indication of the magnitude of this source of variability, crack growth data from 68 tests of identical specimens under an identical constant amplitude loading environment were analyzed. The test program is described in Reference 9. Figure 16 reproduces the 68 crack length curves as a function of number of applied cycles (time). Assuming these curves are representative of crack growth variability in identical crack growth gages, it can be seen that the variability in crack length at fixed time increases with time and becomes significantly large. To quantify the variability, the mean and standard deviation of crack length were calculated at 70,000, 140,000, and 210,000 cycles. These values are given in Table 8.

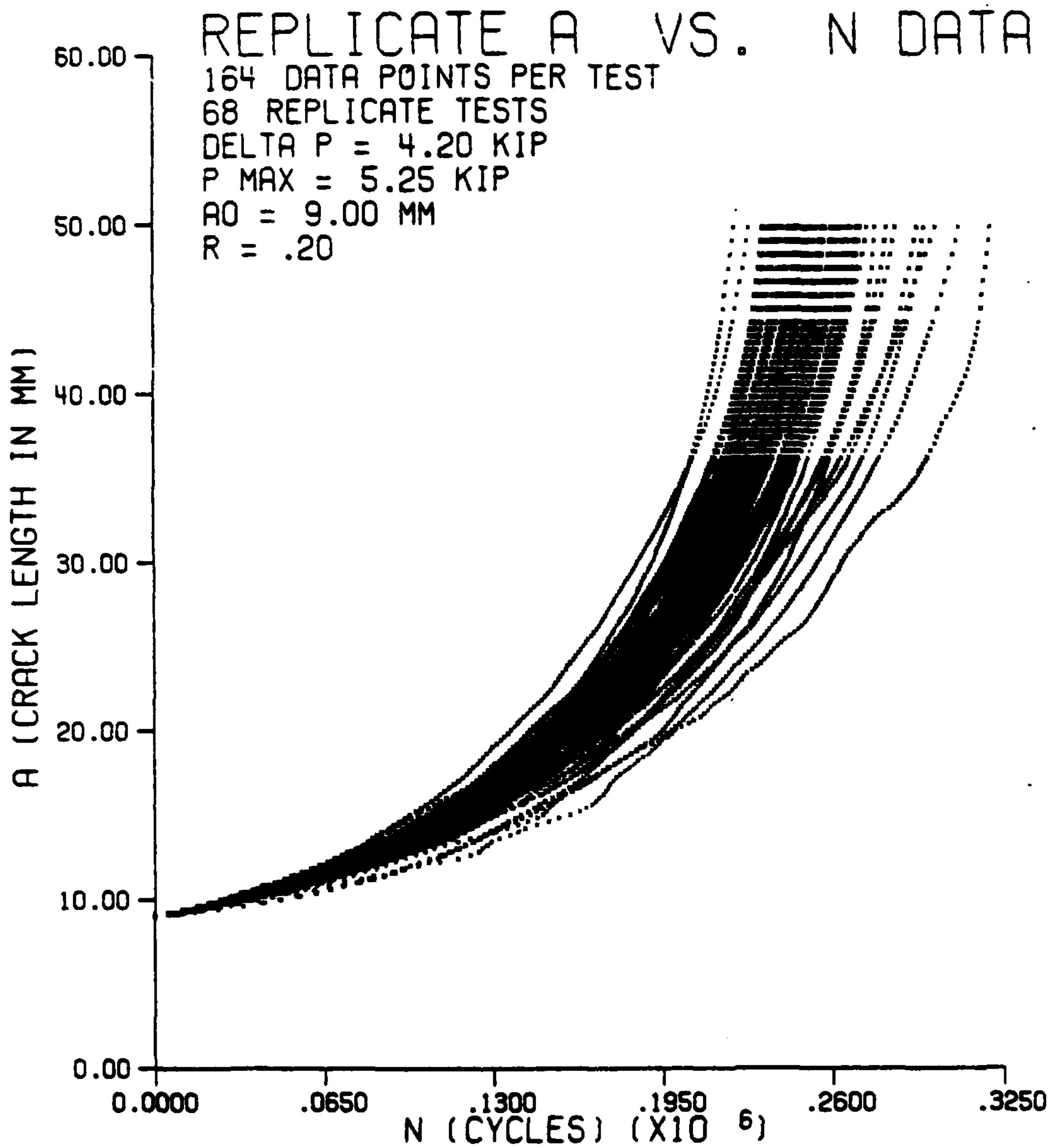


Figure 16. Fatigue Crack Growth (a vs. N) Data from 6B Replicate Tests on 2024-T3 Aluminum Alloy (0.100 inch Thick Center Crack Panels).

TABLE 8

CRACK LENGTH VARIABILITY OF IDENTICAL SPECIMENS UNDER IDENTICAL STRESS ENVIRONMENTS

	TIME (CYCLES)		
	70,000	140,000	210,000
Average Crack Length (mm)	11.83	17.21	29.01
Standard Deviation (mm)	0.394	1.19	3.36
Coefficient of Variation	0.033	0.069	0.116

In a practical application the variability due to the correlation between gage crack length and critical location would be added to the gage to gage variability.

SECTION 4

LOADS/ENVIRONMENT SPECTRA SURVEY FUNCTION

The Loads/Environment Spectra Survey (L/ESS) function is concerned primarily with the collection and processing of usage data from aircraft performing representative operational flights. The L/ESS function does not directly impact decision making but rather provides a data base primarily for (1) checking assumptions previously made about the operational stress spectrum and (2) updating (when necessary) the durability and damage tolerance analyses (DADTA) and the force structural maintenance (FSM) plan. (On occasion, L/ESS data have also been used as a supplement in IAT programs but this is not considered to be a primary function.) Figure 17 presents a schematic of the L/ESS function through the requirement of the initial L/ESS. Updating the DADTA and FSM plan are not analysis requirements of the L/ESS function. However, developing the operational spectra and comparing the current operational spectra with the previous are clearly identified L/ESS functions. Monitoring for usage change can be an L/ESS function but may also be accomplished on the basis of other data.

According to MIL-STD-1530A, the "objective of the loads/environment spectra survey shall be to obtain time history records of those parameters necessary to define the actual stress spectra for the critical areas of the airframe." The prevailing connotation of this objective has been a large data set which contains statistical summaries of loads parameter and/or stresses stratified by flight conditions (mach number, weight, altitude, configuration) and mission description (mission type or segment, base of operation, command). Such data sets can also be used to summarize how the aircraft are being flown to generate the stress cycles which influence the potential crack growth at a critical location. Recently, L/ESS programs are also being considered based on monitoring only strain cycles at one location.

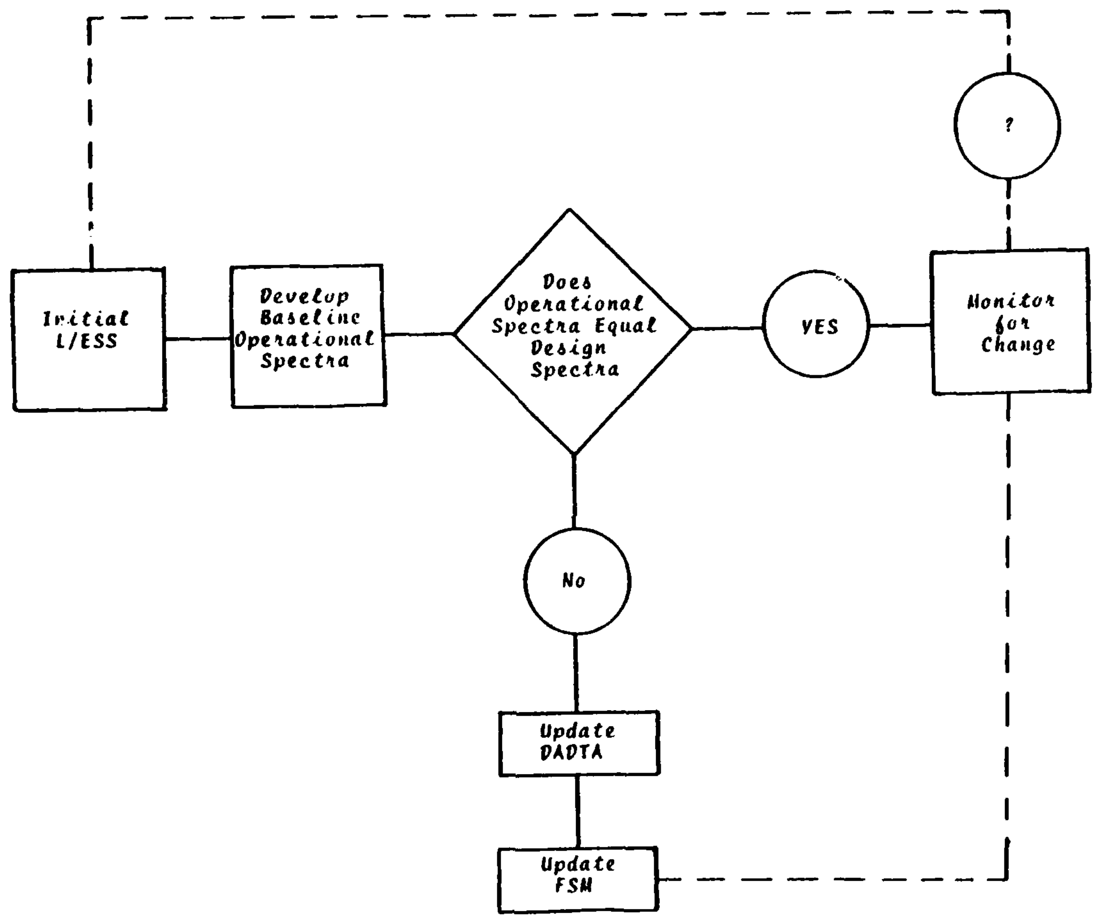


Figure 17. Schematic of Initial L/ESS.

In the following paragraphs, several aspects of the L/ESS function are addressed which are related to the problems of data collection and processing. The particular topics to be addressed are sample size evaluation in L/ESS; usage change detection; mission descriptions; design criteria data; and duration of the L/ESS.

4.1 SAMPLE SIZE CONSIDERATIONS

The loads, strains, flight condition and mission parameters which are usually construed as L/ESS type data exhibit considerable variability from flight to flight under routine operational usage. Under the best of circumstances, this variability makes it difficult to decide if the spectra in one period is different from that of design or a different period. Further, a typical spectra is defined in terms of a large number of distributions of the relevant load parameters for the flight condition and mission categorizations of interest. The combination of these complicating factors has inhibited the definition of criteria for identifying changes in operational spectra. Hence, there is no commonly accepted analytical techniques for testing equality of operational spectra (i.e. detecting changes) or for determining the required amounts of data to yield sufficient precision in the estimated spectra. An analytical approach to the sample size problem, based on the metric of Miners damage per flight, was formulated in References (10) and (11). Although this metric is unacceptable under the current damage tolerance approach to structural integrity, these reports present discussions of the problem of obtaining random samples in the stratifications of interest which are applicable to any monitored metric.

In the following, a crack growth based metric is proposed as a possible parameter for analytically determining the quantity of data required by an L/ESS program to achieve a given degree of precision in the metric. The parameter can also be used in a statistical test for changes in operational spectra. The discussion will center on potential crack growth at one control point but the analysis considerations can easily be generalized to multiple locations.

It is generally recognized that the L/ESS function is achieved by monitoring only a sample of all possible flights of the particular force of interest. Thus, it is necessary to assume that any particular sample of monitored flights is a random (representative, unbiased) sample for some population of interest. The economics of data collection for sampling operational usage dictates that the data sample will be obtained from the flights of a fixed set of instrumented aircraft. If the recorded flights are reasonably representative of total fleet operations, then the sample will be completely random and statistical inferences can be made without stratifying the population of all flights into sub-populations. However, it is common for certain mission types to be disproportionately represented in a sample of monitored flights (as determined by comparison with an independent data source). In this case, the monitored flights are representative only within stratifications of the population of all flights. Some example stratifications are divisions defined in terms of mission types, mission by base combinations, mission segment by mission design series, etc. Inferences made for a group of airplanes are then made by combining the results from individual stratifications. Note that the stratifications, if any, must be defined by an analysis of the operations to be sampled and the extent of the inferences to be drawn from the sample. In the following it will be assumed that a random sample of operations from one stratification will be obtained. Methods of combining data from several stratifications are described in References 10 and 11.

To develop an analytical approach to sample size determination and usage change detection in L/ESS, it is necessary to define a metric which is (1) relatable to design or previous operational usage spectra, (2) descriptive of severity of operational usage, (3) calculable as part of a routine L/ESS output, and (4) has known statistical properties so that inferences can be drawn regarding sample sizes and usage changes. One such metric that has these properties is the estimated potential crack growth during a flight given one fixed crack length at the start of all flights.

Assume that

$$\frac{da}{dn} = b\ [f(K)]^m \tag{30}$$

where

$$f(K) = f_2(a) \cdot f_1(\sigma) \tag{31}$$

This model assumes the crack growth rate is an exponential function of the stress intensity factor and that the stress intensity factor can be separated into a crack length component and a stress component. For example, in Paris' equation

$$\begin{aligned} f(K) &= \Delta K \\ &= \beta(a)\ \sqrt{\pi a} \cdot \Delta\sigma \end{aligned} \tag{32}$$

and

$$f_2(a) = \beta(a)\ \sqrt{\pi a} \tag{33}$$

$$f_1(\sigma) = \Delta\sigma \tag{34}$$

where $\beta(a)$ depends on crack length and geometry. During flight i, an aircraft will experience N_i load cycles at the potential crack site and a potential crack will grow an increment Δa_i where

$$\Delta a_i = \sum_{j=1}^{N_i} \Delta\ a_{ij} \tag{35}$$

and $\Delta\ a_{i,j}$ is the crack extension due to the jth stress cycle in the ith flight. Assume that the potential crack has length a_o at the start of each flight and that a negligible error results if crack length at the start of the flight is used to calculate all increments during the flight. Then

$$\Delta a_i = \sum_{j=1}^{N_i} b \; f(K_{ij})^{m}$$

$$= \sum_{j=1}^{N_i} b \, [f_2(a_o) \cdot f_1(\sigma_{ij})]^m \tag{36}$$

$$= b \, [f_2(a_o)]^m \sum_{j=1}^{N_i} [f_1(\sigma_{ij})]^m$$

The potential crack growth for the fixed length is proportional to a function which depends only on the stress cycles encountered during the flight. Since the number and magnitude of the stress cycles encountered in a randomly selected flight are random variables, the quantity

$$X_i = \sum_{j=1}^{N_i} [f_2(\sigma_{ij})]^m \tag{37}$$

is a random variable which describes the severity of the flight and is crack growth based. Since N_i is not necessarily large, the distribution of X_i will not be known in general (even though it is modeled as a sum of random variables). However, it is possible to empirically determine distributional properties of X_i over many flights and compare these with the equivalent properties from the design or previously used operational spectrum to test for changes in usage. Further, analytical sample size considerations could be approached from the view-point of determining the required number of flights to estimate the average X_i within a pre-specified degree of precision.

Before discussing these concepts further, two points should be noted with respect to the activity indicator of Equation (37). In Reference 12, "Improved Methods for Predicting Spectrum Effects - Phase I Report," the authors propose a characterization of random spectra in terms of the parameter,

$$K = (\overline{\Delta \; \sigma^b})^{1/b} \quad \Psi(a) \tag{38}$$

"where $\overline{\Delta\sigma^b}$ represents the statistical average of the bth power of the stress rise $\Delta\sigma$ in the stress history and $\Psi(a)$ is a function of crack size a, whose analytical form depends on the crack shape". The results of this study indicate that the average X_i may well provide a relevant indicator of usage activity.

In a somewhat different context, General Dynamics has modeled crack growth in terms of the function,

$$\frac{da}{dt} = Q\,[a(t)]^b \; . \tag{39}$$

They have concluded that the parameter b is "fairly well behaved for most FHQ (Fastener Hole Quality) data sets. In most cases, b is approximately 1.0", Reference 13, p. 13. With the parameter b equal to unity an exponential crack growth model results as discussed in Reference 14. In fact, in Reference 14 it is shown that (with b=1) the potential crack length at the end of t flights is given by:

$$a_t = a_o \exp\{Q\,X\,(t)\} \tag{40}$$

where

$$X(t) = \sum_{i=1}^{t} X_i \tag{41}$$

In this formulation, X(t) will have approximately a normal distribution for large t, with mean and variance given by

$$\begin{aligned} E[X(t)] &= t\,E\,(X_i) \\ \text{var}\,[X(t)] &= t\,\text{var}\,[X_i] \end{aligned} \tag{42}$$

Therefore, the distribution of the predicted crack length can be modeled in terms of the mean and standard deviation of the activity indicator of Equation (37).

The activity metric defined by Equation (37) is directly proportional to the potential crack growth during a flight or flight segment of a crack of fixed initial length. Define this as the standardized crack growth rate metric. The standardized crack growth during any one flight or flight segment will be unknown but can be described as a random variable. Past experience with other such metrics indicates that the distribution of X will be highly skewed (to the large crack growth per flight side) with a large standard deviation as compared to the mean. If the average of the distribution of standardized crack growth rates is taken as the measure of operational usage during a flight or flight segment, the objective of the L/ESS can be interpreted as estimating this average. Further, the precision of the estimate is determined by the number of sampled flights or flight segments so that given some estimate of the standard deviation of standardized crack growth rates a sample size can be predetermined to yield a desired degree of precision with a desired degree of confidence or, conversely, given a sample size the degree of precision can be estimated.

Note first that for practical purposes it will be sufficient to define $f_1(\sigma)$ as the maximum stress in a cycle (σ_{max}) or the change in stress during a cycle ($\Delta\sigma$). If a relatively constant stress to normal acceleration (n_Z) relationship exists for the critical point of interest, the standardized crack growth rate metric is equivalent to Σ (peak $n_Z)^m$ or $\Sigma(\Delta\, n_Z)^m$. In more complex response locations, it will be necessary to first calculate (or measure) the stress response at the location of interest before calculating the metric. Thus, strain at (or near) the monitored locations would be reasonable parameters to monitor in this latter case.

Assume that a random sample of k flights (or excursions into a flight segment) will be monitored and for each flight the standardized crack growth rate metric, X_i, will be calculated. Under the assumption that the sample is representative of a fixed population, the X_i can be used to estimate the statistical properties of the population. In particular, assume that the usage

being monitored can be summarized by the mean, μ_X, of the population of metrics. In this formulation, it is quite simple to determine the number of flights to be monitored to achieve a specified level of precision with a given level of confidence, if k is sufficiently large.

If k>30, it can be assumed that the distribution of

$$\bar{X} = \frac{1}{k} \sum_{i=1}^{k} X_i = \frac{1}{k} \sum_{i=1}^{k} \sum_{j=1}^{N_i} (f_1(\sigma_{ij})^m \tag{43}$$

is approximately normal with mean and standard deviation given by μ_X and $S_X/\sqrt{k}$, respectively. Two sided, 100 (1-α) percent confidence bands on the true average standardized metric are calculated from

$$P\{ \left| \frac{(\bar{X} - \mu_X)\sqrt{k}}{S_X} \right| < Z_\alpha\} = 1-\alpha \tag{44}$$

where Z_α is obtained from a normal distribution with zero mean and unit standard deviation. Then

$$P\{ - \frac{Z_\alpha S_X}{\sqrt{k}} < (\bar{X} - \mu_X) < \frac{Z_\alpha S_X}{\sqrt{k}} \} 1-\alpha \tag{45}$$

or

$$P\{ - \frac{Z_\alpha S_X}{\sqrt{k}\ \mu_X} < \frac{\bar{X} - \mu_X}{\mu_X} < \frac{Z_\alpha S_X}{\sqrt{k}\ \mu_X} \} = 1-\alpha \tag{46}$$

This inequality expresses the imprecision in the estimate of the mean in terms of percent error. Define the percent error confidence bound, E, as

$$E = \frac{Z_\alpha\ S_X}{\sqrt{k}\ \mu_x} (100) \tag{47}$$

or equivalently

$$k = [\frac{Z_\alpha}{E}(100)\ C]^2 \tag{48}$$

where C is the coefficient of variation

$$C = \frac{S_X}{\mu_X}$$

Equation (48) can be used to determine the sample size to achieve desired precision for fixed confidence and coefficient of variation. For example, Figure 18 is a plot of percent error confidence bound versus sample size for 95 percent confidence and various coefficients of variation of the standardized crack growth rate metric. The values of C span the ratios of standard deviation to mean that would be expected in field data based on past experience with the metric of Miner's damage per flight. As a guideline, Table 9, from Reference (11), presents observed coefficients of variation that were obtained using Miner's damage per flight. These values indicate the scatter that will be present in the per flight standardized crack growth metric as both are strongly correlated with n_z. Smaller values would be expected if a sample is defined by each excursion into a flight segment.

As an example of the interpretation of the data in Figure 18, assume that the coefficient of variation for the usage metric is 2.0. Then to be 95% sure that the average crack growth rate metric will be within 10 percent of the true value will require a sample of 1536 flights. Conversely, if a data sample of 500 flights is available, then there is 95% confidence that the true metric is within 17.5 percent of the observed.

Several points should be made regarding the use of Equation (48) or Figure 18. Recall that the inference is valid only over the population for which a random sample was obtained. Thus, if in a given L/ESS program, the data are considered to be random samples for each mission types, the mission characterization precision can only be defined in terms of the number of flights of each mission type. It should also be noted that it is not necessary to have the same precision for all stratifications.

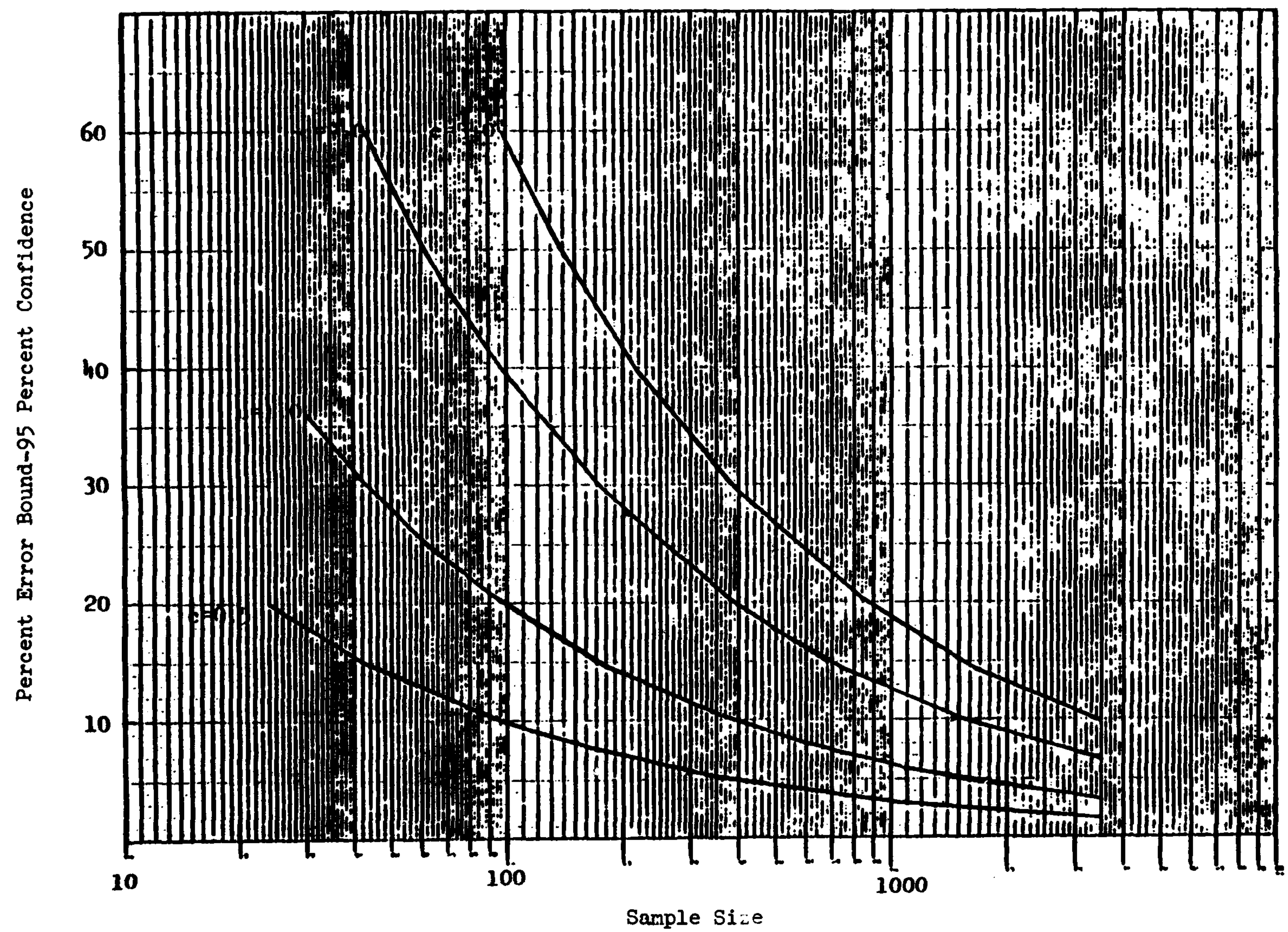


Figure 18. Sample Size to Achieve Specified Precision with 95 Percent Confidence

TABLE 9

DAMAGE PER FLIGHT STATISTICS FOR THREE AIRCRAFT TYPES

Aircraft Type	Mission Type	Per Flight Average $\bar{D}$	Coefficient of Variation[a] C	Sample Size k
F-105D	Combat	2.9×10^{-4}	2.3	1317
C-135	Cargo	5.8×10^{-6}	1.9	822
	Training	16.3×10^{-6}	1.1	199
	Weather	27.3×10^{-6}	1.7	148
T-38	Training	31.2×10^{-6}	1.0	1941
	Formation	19.0×10^{-6}	1.3	234
	Nav. & Gen.	2.8×10^{-6}	3.0	1529
	Admin.	11.0×10^{-6}	1.6	144
	Composite	18.4×10^{-6}	1.3	3848

[a] Coefficient of Variation, $C = S_D/\bar{D}$.

If, for example, certain mission types are far less damaging than others, less precision could be tolerated in the standardized crack growth metric. These ideas are further expanded in References (10) and (11) and their ramifications will not be further pursued.

The above sample size determinations yield the number of flights or flight segments to be monitored to achieve the desired precision. It is assumed that sufficient precision in the standardized crack growth rate metric will also imply sufficient precision in the distributions of loads parameters that result from the monitored flights. The desired precision is achieved from a random sampling of all flights or flight segments within the population and, thus, is independent of the number of instrmented aircraft and/or the time period over which the flights are monitored. These decisions will have to be made on the basis of engineering judgement of the time frame during which decisions will be required. These decisions will also be influenced by the capture rate of valid data that can be expected for the particular aircraft and recording system.

MIL-STD-1530A also specifies that the "Air Force will also be responsible for ensuring that survey data are obtained for each type of usage that occurs within the force (training, reconnaissance, special tactics, etc.)" For some aircraft types, this requirement poses no particular problem as the usage need only be obtained for a few stratifications as defined by, say, mission types. For others, however, the usage is extremely diverse and there are so many mission design series that considerable care must be exercised in the allocation of monitoring equipment to aircraft. Further, it may also be necessary to monitor usage for considerably longer periods of time to obtain a desired degree of precision. Regardless, the above formulation can be used to determine the number of flights that should be monitored or conversely to evaluate the precision given a fixed number of monitored flights.

4.2 USAGE CHANGE DETECTION

In addition to defining the operational usage stress spectra, MIL-STD-1530A also indicates that the L/ESS function includes a proposed "method to be used to detect when a significant change in usage occurs to require an update in the baseline operational spectra." An optional approach to usage change detection is available if the appropriate data is available as part of the IAT program. Historically, usage changes have been interpreted in terms of changes in exceedance distributions for some level of stratification of the total population of potential uses. Emphasis has shifted, however, to considering changes which can impact the monitoring of potential crack length to reach a pre-defined size. Thus, usage change detection should be defined in terms of parameters which occur at the interface between both the IAT and the FSM portions of force management.

Viewed in this light there cannot be a universal answer to usage change detection. In transport/bomber tracking, the basic element of data collection is the pilot log. With this source of data for tracking, potential crack growth rates by data block (loosely defined) are the essential parametric input as mission type and time in data block are directly monitored. Thus, the stress histories within the data blocks are the key parameters for feeding the tracking program and projections of crack growth are based on predicted amounts of time in data blocks. Contrast this situation with a counting accelerometer based tracking system in attack/fighter/trainer aircraft in which the accelerometers are read monthly. In this type of program, potential crack growth and predicted crack growth are both dependent on assumptions regarding mission mix (weights and configurations) as well as severity of usage while performing the missions.

In the following paragraphs, usage change detection is considered as a function of either the L/ESS or the IAT programs. Note that usage changes might also be detected by comparing planned and current flight operations.

4.2.1 Usage Change Detection From L/ESS Data

While recognizing that usage change detection must be tailored to meet individual needs, the standardized crack growth metric, defined by Equation (47), can provide a basis of comparison of magnitudes of stresses within a stratification. As noted earlier, this metric is proportional to a predicted crack growth of a crack of fixed length, can be easily calculated (particularly if stresses are being monitored as part of the L/ESS or IAT systems), and can be calculated for an entire flight or for shorter segments as defined by data blocks if desired. When calculated for operational aircraft, the metric can be considered as a random variable which measures the severity of usage in crack growth terms. One part of the question of usage change detection can be approached by this metric by comparing its distributional properties observed in the field with equivalent properties of the design or baseline spectra.

While the data are not available to present detailed examples, the application of this metric for usage change detection would be straightforward for a particular system of interest. In a forms monitoring application, the key L/ESS output is the measure of the average crack growth for a unit time in a defined flight condition. The data which is used to calculate this input can also be used to generate the average standardized crack growth rate metric. The monitoring operation would consist in calculating the mean and standard deviation of the metric from the operational flights and performing standard statistical tests on the equality of the operational and baseline averages. In an aircraft which has a counting accelerometer based IAT tracking system, stress spectra over much broader stratifications must be considered. Usage severity may be compared as above on the basis of a mission stratification but a comparison of planned and actual mission mixes would also be required. Thus, a significant change in the severity of performing missions could be detected by the tests on the metric and significant changes in mission usage would be detected by tests on equality of mixes. Changes in either of these factors could affect the estimated potential crack length from the IAT and the projected time until a maintenance action is required.

4.2.2 Usage Change Detection From IAT Data

The key output of an IAT tracking program is the estimate of potenital crack length at each monitored location in each airplane of the force. The potential crack length is coupled with a crack length as a function of flight time in baseline usage to arrive at a predicted number of flight hours until the potential crack would reach a length which requires a maintenance action. This process is illustrated in Figure 19. At calendar date, D_i, the airplane has logged t_i^* hours and the estimated potential crack length is a_i. For this crack length, the airplane has flown the equivalent of t_i baseline hours and $t_c - t_i$ baseline hours remain until a maintenance action is indicated. At calendar time D_i, the predicted number of months to maintenance action, Li, can be calculated as

$$L_i = \frac{(t_c - t_i) R}{U} \tag{49}$$

where U is the expected number of flight hours per month and R is a severity factor reflecting possible differences in usage from the baseline spectrum that yielded the FSM plan behavior.

This estimate of calendar months to maintenance action is based on assumptions rega[illegible]ng future usage. If, over a given time period, the usage is consistent with the assumptions, then the projections should also be consistent. (Note that this consistency is defined across the stratification of the total force for which a constant severity factor would apply). On the other hand, if the projections are not consistent over the period, the aircraft are being flown differently than planned and a bias is being introduced into the projected times to maintenance action.

Since the planned usage (FSM crack growth behavior) is defined for an "average" aircraft, any changes in usage must be detected by considering changes in projected months to maintenance actions across a population of aircraft. Figure 20 illustrates the calculation of months to maintenance action for airplane j at the

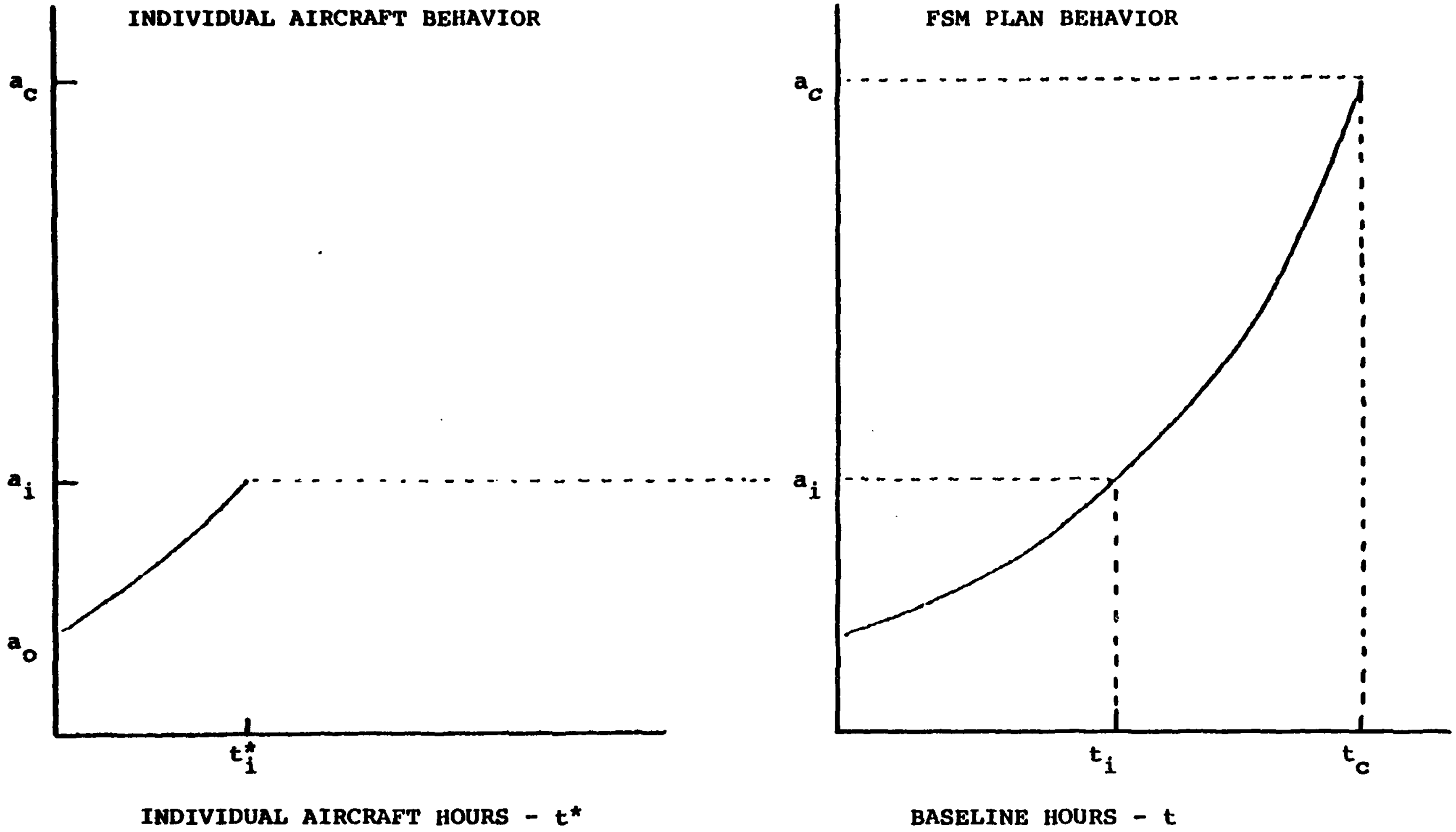


Figure 19. Correlating Individual Aircraft Usage to Baseline Usage.

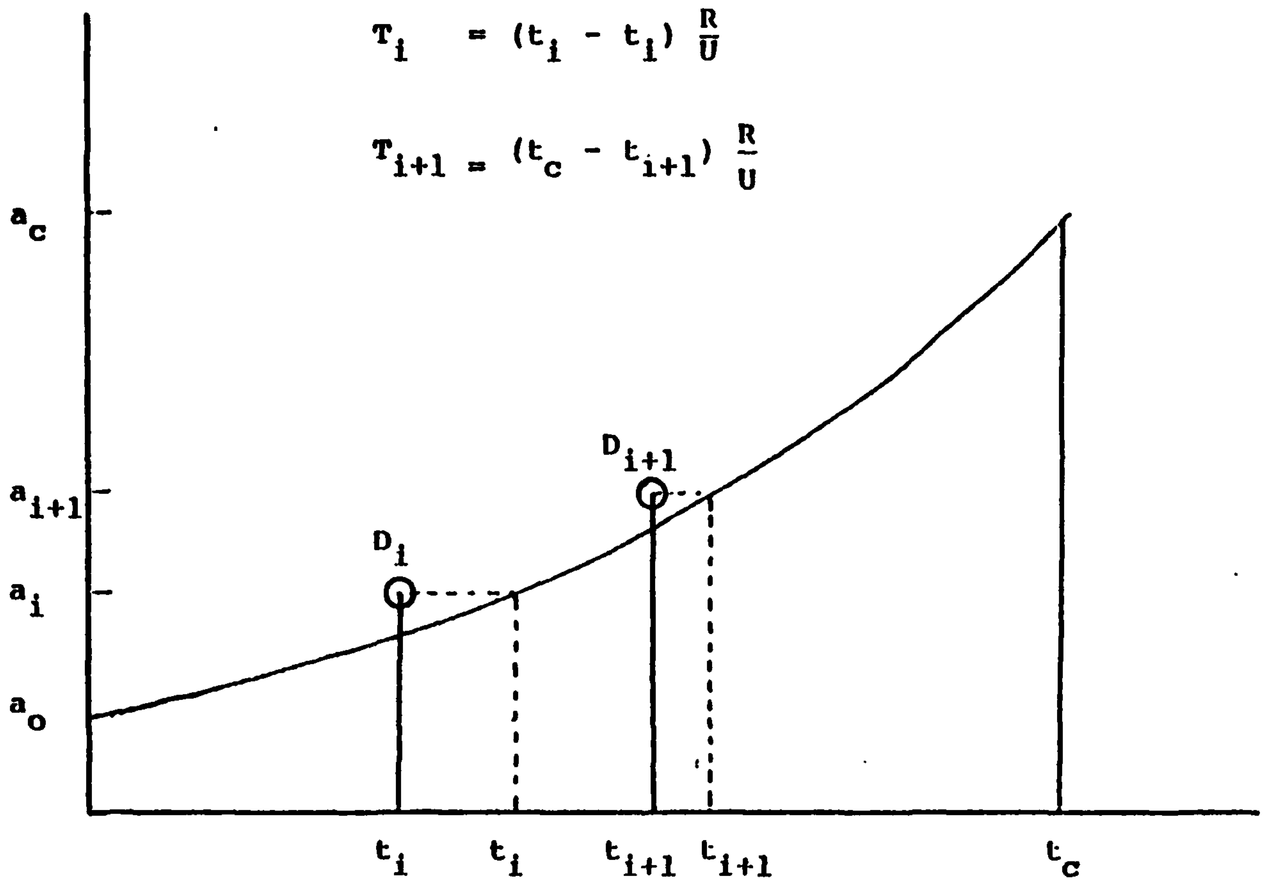


Figure 20. Prediction of Calendar Time Until Maintenance Action at Two IAT Updates.

ith and (i+1) the update of the IAT program. If this airplane had flown exactly as planned then the projected date of the maintenance action would not change. That is, if the IAT updates are 6 months apart then the predicted calendar months to maintenance action would differ by 6 months. More generally,

$$T_{i,j} - T_{i+1,j} = D_{i+1} - D_i \tag{50}$$

Since the tracking program is updated for all aircraft at the same time, the months between updates does not depend on the individual aircraft and is known exactly (e.g. 6 months). Therefore, by considering the differences in projected months to maintenance actions $(T_{i,j} - T_{i+1,j})$ to be a random variable, the statistical properties of $(T_{i,j} - T_{i+1,j})$ can be analyzed. In particular, a test of the hypothesis

$$H_o: \overline{T_{i,j} - T_{i+1,j}} - (D_{i+1} - D_i) = 0$$

versus

$$H_1: \overline{T_{i,j} - T_{i+1,j}} - (D_{i+1} - D_i) \neq 0$$

can easily be performed for those stratifications for which there are sufficient aircraft to assume normality of the sample averages. This formulation assumes that the experience of the individual aircraft in the period is representative for the population and that the severity of usage in one period is independent of that in the next. An example of the application of this test and a demonstration of the validity of the independence assumption is presented below.

Note that if the test indicates a significant difference between maintenance dates for the two periods, a follow-up analysis will be required to determine if the difference is due to the flying rate or the severity factor. A test on the average flying rate could easily be performed since the total flight hours of each individual aircraft are routinely reported at each IAT output.

As an example of the application of this trend analysis of usage, recent IAT data from an A/F/T Aircraft (Reference 5) were analyzed. Since tracking reports on each airplane were available over a several year period, remaining years to potential critical crack length were calculated for each of four updates separated by six-month intervals. The IAT updates were dated January 1978, July 1978, January 1979, and July 1979 and spanned 3 time periods of activity.

Cumulative distributions of the time to potential critical crack lengths for the four time periods are presented in Figure 21. The variability in any one of these curves reflects the individual usage as well as the age of the aircraft, i.e. the baseline ages. If usage in each of the three periods was as planned, then the four curves would be offset by 0.5 years. As can be seen in the figure, this is approximately true.

To test the significance of the changes in predicted times to maintenance actions, the differences were calculated for each aircraft in each of the three time periods by means of the formula

$$\Delta_{ij} = T_{i,j} - T_{i+1,j} - 0.5 \tag{51}$$

where i = 1, 2, 3 and j is an index on the individual aircraft. Cumulative distributions of the differences for the three time periods are presented in Figure 22. Since no changes in planned usage would correspond to an average difference of zero, this hypothesis was tested for the three periods with the results as summarized in Table 10. The results of the test indicate that usage was consistent with planned during the first two periods but was more severe during the third period. Note that the average change in predicted average time to maintenance action is about 2 months which may not be practically significant.

To test the assumption of independence of usage in consecutive time periods, the differences for each airplane were correlated between time periods. Figure 23 presents the scattergram for the correlation between the first and second time periods.

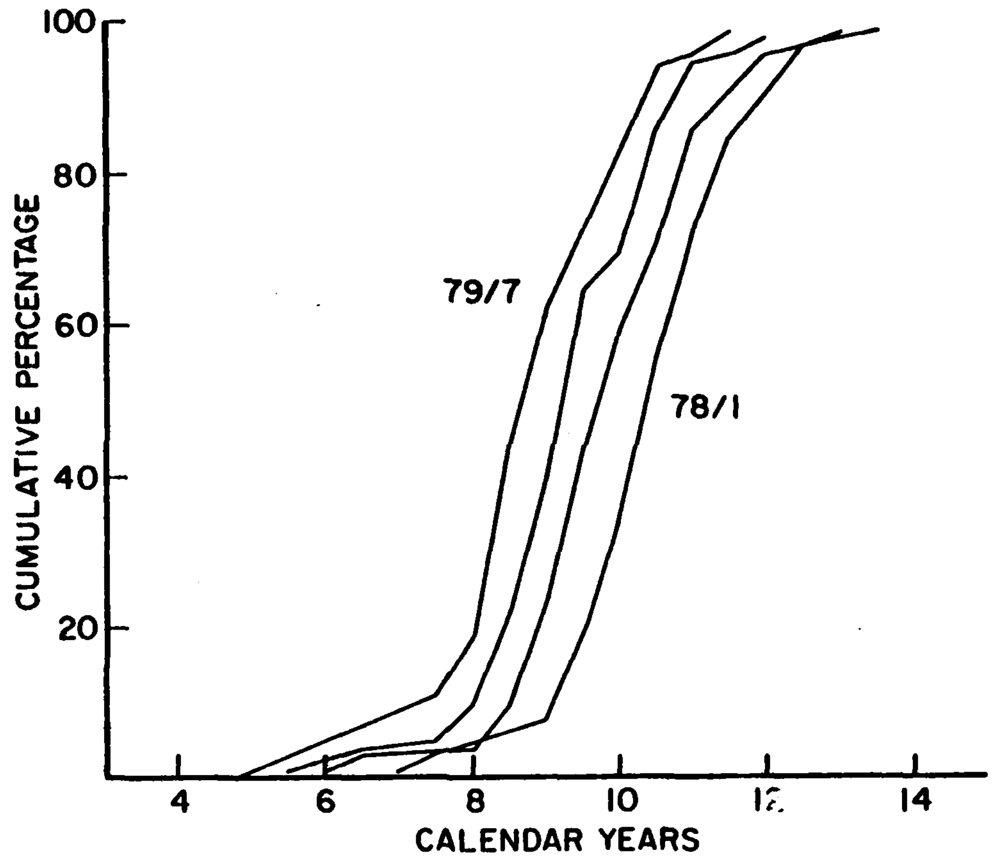


Figure 21. Distributions of Predicted Times To Maintenance Actions.

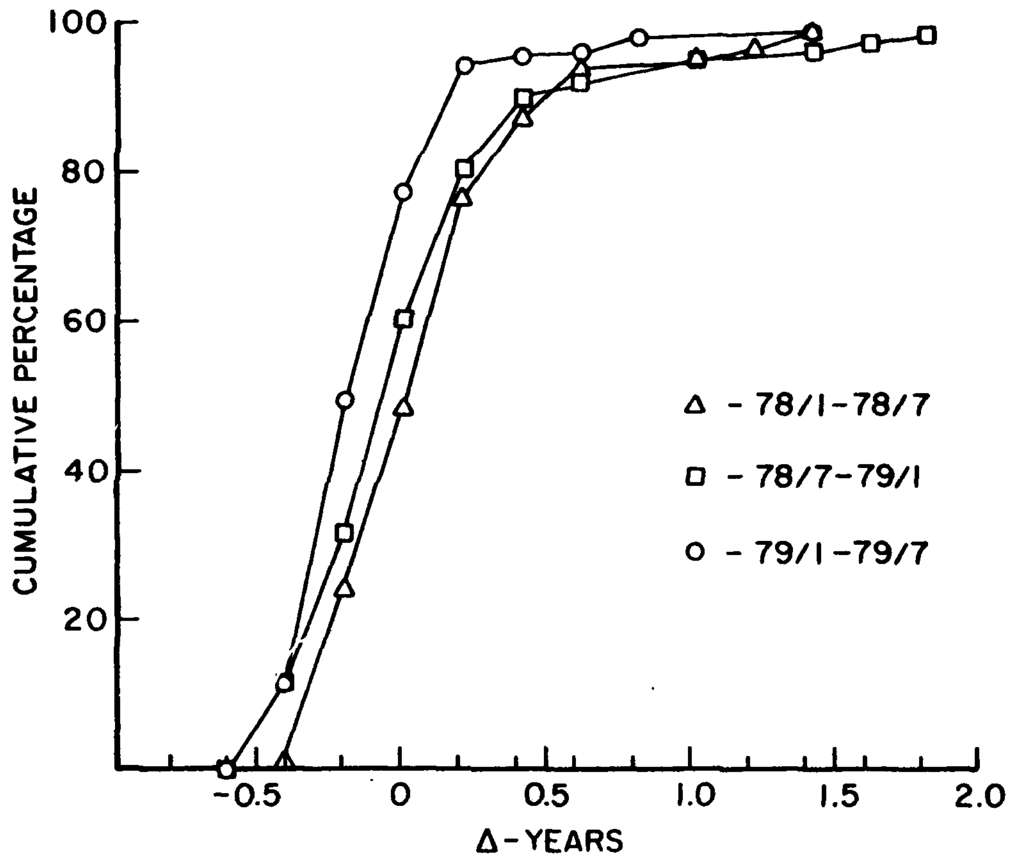


Figure 22. Cumulative Distributions of Differences in Projected Dates for Maintenance Actions.

TABLE 10

TESTS OF SIGNIFICANCE OF USAGE CHANGES IN THREE PERIODS - EXAMPLE A/F/T DATA

	Period 1 (78/1-78/7)	Period 2 (78/7-79/1)	Period 3 (79/1-79/7)
$\overline{\Delta}$	0.06	0.00	-0.15
S_{Δ}	0.36	0.43	0.29
$S_{\overline{\Delta}}$	0.041	0.050	0.033
Student's t	1.46	0.0	-4.6*

*Statistically significant at 99 percent level.

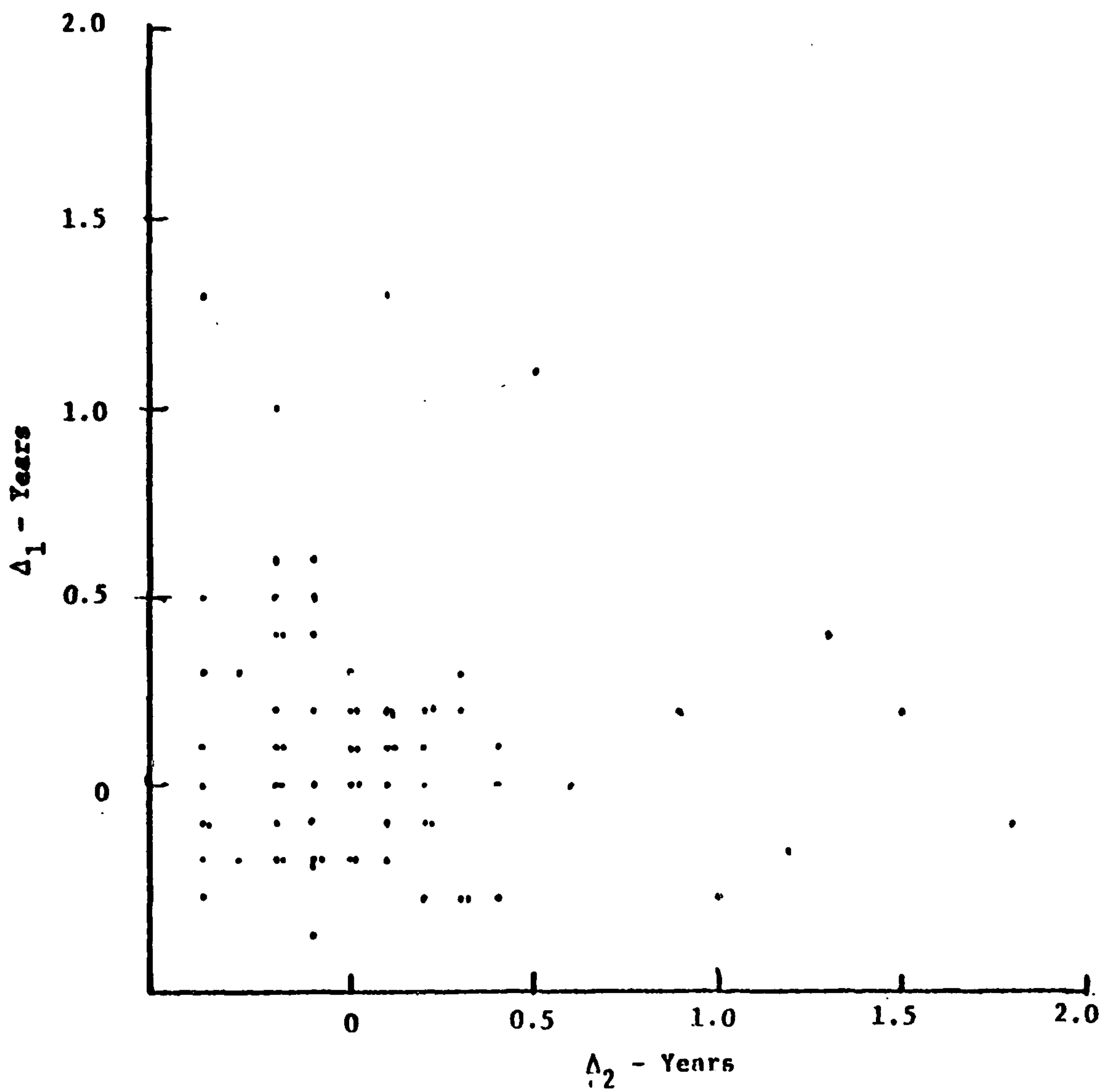


Figure 23. Correlation of Change in Projected Maintenance Dates Between First and Second Time Periods.

This was the strongest correlation among the three pairs and produced a correlation coefficient of $r = 0.06$. Therefore, at least for this aircraft, the severity of usage is independent between consecutive time periods.

4.3 DESIGN CRITERIA DATA

The AFR 80-13 requirement to provide structural design criteria data has generally been interpreted to belong to the L/ESS function of MIL-STD-1530A. The following paragraphs briefly summarize the design criteria data requirements.

The design durability and damage tolerance analyses of a new aircraft system are dependent on the sequence of repeated loads the aircraft will experience during its lifetime. To specify this sequence, it is necessary to have an estimate of the number and severity of the load occurrences which will be encountered. These are obtained from a combination of the desired usage of the new aircraft and observed usage of current similar aircraft.

The desired usage of a new aircraft system is defined in terms of the expected frequencies of mission profiles the aircraft will fly during its lifetime. Each profile defines time histories of airspeed, altitude, and weight as well as stores configurations, average fuel usage, number of pressurization cycles and number of touch-and-go landings. This information provides the basis for the flight conditions used to compute the loads and the total time for each flight condition which allows eventual determination of the number of load occurrences. Figures 24 and 25 show one method of presenting mission profile data (Reference 15).

The observed usage of current aircraft provides load frequency and relative magnitude information. This is given as the number of exceedances of a given load level, as indicated by the peak load factor, n_z, for a reference flight time. The reference flight time has usually been taken to be 1000 hours for convenience. Figure 26

T-38 ATC MISSION PROFILE

MISSION: Basic Instrument ENVIRONMENT: Air Training Command

PHASE	POWER SETTING	POINT	WEIGHT LB. INCR.	WEIGHT LB. GROSS	TIME MIN. INCR.	TIME MIN. TOTAL	SPEED TRUE	ALTITUDE FT. MSL
TAXI		START		12216				
		END	54	12162				1000
TAKE-OFF	MAX	START	342		2		155 KCAS	
		END		11820		2	155 KCAS	1000
CLIMB	MIL	START	350		8		350 KCAS	
		END		11470		10	350 KCAS	30000
CRUISE	1900 LB/HR	START	158		5		350 KCAS	
		END		11312		15	250-350 KCAS	30000
PRIMARY	2307 LB/HR	START	769		20		250-350 KCAS	
		END		10543		35	350 KCAS	26000 TO 32000
CRUISE	1850 LB/HR	START	154		5		350 KCAS	
		END		10389		40	350 KCAS	30000
DESCENT	PENETRATION PLUS PATTERN	START	1433		33			
		END		8956		73		1000
TAXI		START						
		END						
		START						
		END						

Total Fuel Wt. = 3960 lb.
Internal Fuel Wt. = 3960 lb.
External Fuel Wt. = lb.
Pylon Tank Wt. = lb.

TAKE-OFF CONFIGURATION = BASIC
LANDING FUEL RESERVE = 700 lb.

Figure 24. Sample Mission Profile Data.

Mission	Percent	Mission	Phase Time			Configuration	CW	NUMBER	
	Lifetime	Phase	Min.	% Miss.	% Mix		LBS	of Flts	
Basic	9.20	Take-Off	2	2.74	0.252	BASIC	11991	76	
Inst.		Climb	8	10.96	1.008		11645		
		Cruise	5	6.85	0.630		11391		
		Primary	20	27.40	2.521		10928		
		Cruise	5	6.85	0.630		10466		
		Descent	33	45.20	4.159		9673		
Alter.	4.90	Take-Off	2	2.86	0.140	BASIC	11991	42	
Inst.		Climb	5	7.14	0.350		11655		
		Cruise	5	7.14	0.350		11407		
		Primary	20	28.57	1.400		10938		
		Cruise	5	7.14	0.350		10471		
		Descent	33~	47.15	2.310		9673		
Contact	30.80	Take-Off	2	3.03	0.933	BASIC	11991	280	
		Climb	5	7.58	2.333		11655		
		Cruise	5	7.58	2.333		11407		
		Primary	20	30.30	9.334		10949		
		Cruise	5	7.58	2.333		10493		
		Descent	29	43.93	13.534		9684		

T-38 ATC MISSION PHASE FLIGHT PARAMETER DISTRIBUTION

Figure 25. Sample Mission Profile Data.

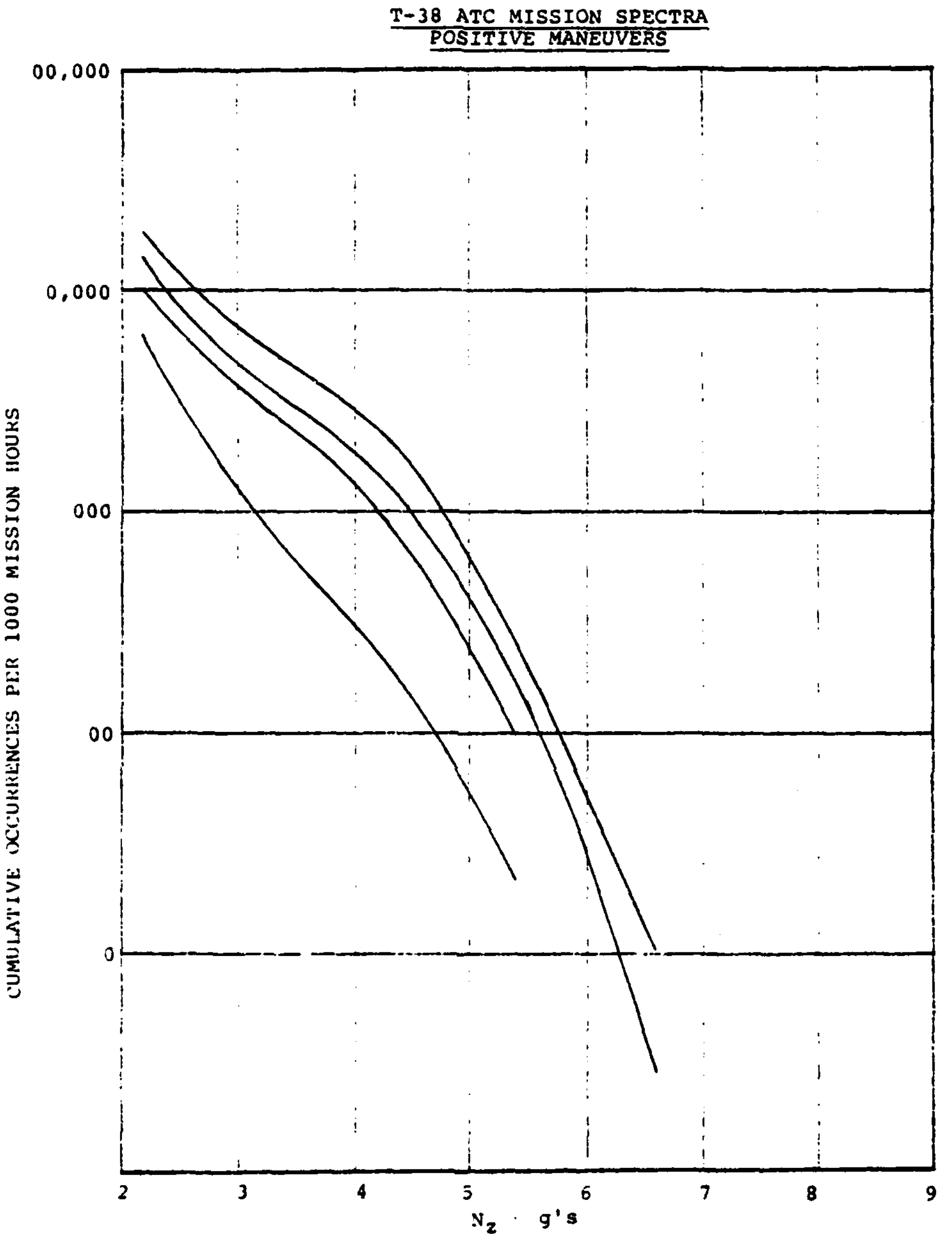


Figure 26. Sample Normal Load Factor Spectra.

shows a sample n_z spectra. Current practice then combines the observed n_z distribution with the mission profile and desired life information to produce a table of occurrences at various n_z levels for each mission. Since each peak n_z value represents a load level, the total predicted number and relative magnitude of the loads for the life of the aircraft are now known.

This information is not sufficient to accurately compute the magnitude of the loads. Still required are the other motion parameters which are coincident with the peak n_z. These include pitch, roll, and yaw angular velocities and accelerations, lateral and longitudinal linear accelerations, and the airspeed, altitude, weight data from the mission profiles. The aircraft motion parameters are typically recorded during L/ESS programs but the data have not generally been processed in a format convenient to the design criteria requirement. Aircraft motion parameters have been found to be conveniently summarized in bivariate tables of n_z or n_y and coincident values of the other parameters. Multivariate data sets can then be reconstructed by computer simulations as in, for example, the Vought Corporation FLISPEC Program (Reference 16).

The design criteria data requirement can easily be met by L/ESS programs if the appropriate output is made a part of the L/ESS function. Further, since sufficient data will be collected during the initial L/ESS to characterize the operational usage of a new aircraft, this quantity of data will be sufficient to specify the joint distributions of motion parameters for design criteria purposes.

4.4 MISSION DESCRIPTIONS

Although not a specific requirement of MIL-STD-1530A, operational mission descriptions are often produced as a data product of the force management system. These descriptions may include such data as numbers of flights and landings and percent time in combinations of missions, mission segments, weight, airspeed, altitude, or configuration for each base of operation. A/F/T aircraft mission descriptions might also include normal load factor exceedance curves for missions, mission segments, or bases. The objective in producing the mission descriptions is to provide a basis for comparison of current with planned usage as defined by mission parameters.

The mission descriptions are generally considered to be an output of the L/ESS. In the T/B aircraft, however, the data required for a mission description is contained in the pilot log form which is the basis of IAT. Such mission descriptions in T/B aircraft are derived as a part of the IAT function. In A/F/T aircraft, the tracking program does not, in general, contain mission data and if a mission description is derived, data from the L/ESS program or some other source would be required. Note that only a relatively small proportion of an L/ESS data set would be required to meet this objective.

4.5 DURATION OF THE L/ESS

MIL-STD-1530A is ambiguous about the duration of the L/ESS program. Beginning with the first production airplanes, the requirement is clear that the L/ESS will continue for 3 years or until one design life of valid data has been collected. After this initial L/ESS and the DADTA update, however, the requirement is to detect usage changes and, if necessary, generate new baseline operational spectra. These latter requirements have been interpreted to imply that the L/ESS will continue with objectives of detecting usage changes and having available a data base for a new DADTA if a significant change is detected. In

view of the large costs associated with the complex process of continuously recording and reducing the multichannel data of L/ESS programs, the potential benefits of these objectives should be reviewed.

From the viewpoint of input in a DADTA, three types of usage changes are significant:

a) an initiation of a new mission or mission segment

b) a change in the magnitude of stress levels

c) a change in the exceedance rate of stress levels

The stress environment in T/B aircraft is governed primarily by mission usage which is monitored on pilot logs or turbulence which is a random property of nature. For this aircraft class a usage change would most probably be defined in terms of different mixtures of time in flight conditions or new mission segments. The former case is handled naturally by the pilot log tracking system with a recalculation required for the projection of potential crack length as a function of time. The latter change would require a characterization of only the new mission segment.

A/F/T aircraft usage changes would be defined only in terms of magnitude and frequency of occurence of stress levels. Both of these types of changes could easily be detected in an IAT system based on stress measurements. If the tracking system were based on load factors, some form of supplementary data would be required to detect changes in the magnitude of stress levels. In particular, a general change in stress levels could result from performing maneuvers at different weights than in the original L/ESS characterization or from modifications to the aircraft which would change the stress response or pilot techniques during the performance of a maneuver. The potential for the latter change would be readily apparent to the ASIP manager. The former could be detected by a periodic review (survey) of operations. In either case, potential changes in usage would be detectable without the operation of multichannel recorders in 10 to 20 percent of a force.

As noted earlier, there is a large degree of scatter in the stress environment of aircraft ostensibly flying the same mission. One result of this scatter is to mask the severity of usage in a period. To detect changes in usage from one period to the next for a particular stratification may require more data than is available from the sample of fleet operations. This is particularly true when the less than 50 percent capture rate of L/ESS programs is considered. Therefore, it is doubtful that usage change detection will be accomplished statistically from L/ESS data. Rather, if it is accomplished from this data source, it will be the result of unusual response at an unexpected time (e.g. the introduction of a refueling mission segment) which can also be detected from other sources.

The above paragraphs indicate that the objective of usage change detection can not only be met by data from other sources but, in fact, may be more efficiently met by the other data sources. Since the L/ESS system is very expensive as compared to a system designed around IAT, aircraft records or periodic questionnaires, it is also more cost effective to use the other data sources.

Beyond the requirement of usage change detection, the objective of a continuous L/ESS is to have available a start of a database for analysis. This data base has four potential uses:

a) a significant usage change will require a new set of load sequences on which to base the DADTA;

b) an unexpected or unusual structural problem at a base could lead to an analysis of the usage at that base;

c) the monitoring of mission descriptions;

d) the development of design criteria type data.

If a change has occured that is of sufficient magnitude that a new DADTA will be required, (e.g. a major structural modification), it will also be of sufficient magnitude that data from before the

change will not be mixed with data after the change. In this case a new L/ESS would be planned and initiated so that L/ESS data would be available for the new load sequences. If only a new mission segment is introduced, only that segment need be monitored and all other representations would be as originally determined.

The second and third potential uses are quite similar and are a valid reason for continuing an L/ESS type program for A/F/T aircraft. (For T/B aircraft, this information is better obtained from the IAT data base.) However, these objectives would be met by processing only the normal acceleration, airspeed, and altitude data. The time and effort required to collect and process the other parameters are not justified for these uses.

Finally, the data for the design criteria requirements can be met during the initial L/ESS. This requirement does not justify a continuing L/ESS program.

Assuming the existence of an adequate initial L/ESS, an IAT program, and a periodic examination of auxilary data that would indicate usage changes, it would appear that a continuing L/ESS program is not necessary, in general. If it is judged important to monitor operations for a particular force, this function can be accomplished by processing only the data from three channels. Therefore, it is recommended that the L/ESS be required only for the initial characterization of operational usage and for special characterizations during the life of the aircraft. A continuous L/ESS would be permitted but a separate justification would be required. This approach to the L/ESS function effectively makes L/ESS a contractor responsibility and relieves ASIMIS of a massive data processing burden.

SECTION 5
FORCE MANAGEMENT DATA PRODUCTS

Task V of MIL-STD-1530 assigns to the Air Force the responsibility "for deriving individual maintenance (inspection and repair) times for each critical area of each airplane by use of the tracking analysis methods and the individual airplane tracking data." To accomplish this objective, the ASIP OPR will require, as a minimum, current estimates of potential crack lengths for each airplane, a projected crack growth curve for anticipated usage and estimates of future flying rates and severities. However, this minimum data is often not sufficient for the decisions required of the ASIP OPR. Further, the minimum requirements can be met by data formats and presentations which are not convenient for application by the ASIP OPR.

This section discusses different types of data products that could easily be obtained from a force management data package if the desired products are specified early. Different aircraft types will have different data requirements and the varieties of data presentation are endless and a matter of personal preference. Therefore, the discussion is presented as a stimulant for further developments in summarizing the results of force management data.

5.1 CURRENT STATUS

At the time of each IAT update, output will be generated which will describe the current structural status of the force. The current status will be based on estimates of potential crack length (or, equivalently, on damage indices or baseline hours) and a list of these values for each airplane is generally considered to be a mandatory output. Table 11 provides an example of a partial list in which the table is ordered by descending damage index. Other orderings are common as, for example, aircraft serial number or damage index by base or model, etc. Table 12 provides another example of current status in which the tracking history of each aircraft is presented.

TABLE 11

EXAMPLE IAT OUTPUT - LISTED BY ORDER OF DAMAGE INDEX

DEC 10. 1979 AIRCRAFT DAMAGE AND RATES BY DAMAGE INDEX

ACFT SN	BASE CODE	LAST DATE	TOTAL HRS	DMG INDEX	DL HRS	MR YR	DI-YR	DLHR YR	EXC5G YR	EXC6G YR	EXC7G YR	EXC8G YR	DL 1000	DLHR 1000	EXC5G 1000	EXC6G 1000	EXC7G 1000	EXC8G 1000
*****	****	****	*****	*****	***	**	*****	****	*****	*****	*****	*****	****	****	*****	*****	*****	*****
741744	WAAR	7909	1777.2	0.479	1916	226	0.041	162	286.7	34.1	3.36	0.23	0.180	719	1270.5	151.3	14.90	1.03
656223	FFAN	7909	2099.0	0.478	1311	263	0.047	189	331.7	53.0	3.64	0.36	0.179	716	1259.1	201.1	13.80	1.38
700977	GAMH	7904	2250.1	0.478	1913	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
701020	GAMH	7907	2060.9	0.476	1906	296	0.066	265	399.8	75.6	6.56	1.08	0.224	894	1350.5	255.2	22.49	3.64
720212	GAMH	7908	1746.2	0.476	1904	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
701036	WYID	7909	2100.2	0.475	1899	180	0.036	143	230.4	21.6	1.80	0.60	0.199	755	1281.3	120.1	10.01	3.34
720230	GAMH	7909	2348.3	0.475	1902	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
656215	VSRE	7909	2113.0	0.474	1895	260	0.060	241	419.7	67.4	5.27	0.55	0.232	928	1617.0	259.0	20.31	2.10
656230	VSRE	7909	2265.0	0.473	1893	260	0.060	241	419.7	67.4	5.27	0.55	0.232	928	1617.0	259.0	20.31	2.10
700972	XHEA	7909	2349.1	0.473	1892	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
701040	WYID	7909	2332.3	0.472	1886	180	0.036	143	230.4	21.6	1.80	0.60	0.199	755	1281.3	120.1	10.01	3.34
700960	PSIE	7909	2200.0	0.471	1882	230	0.053	210	376.6	50.7	2.79	0.22	0.229	911	1640.8	255.8	12.16	0.53
700946	TUMR	7909	1923.0	0.470	1982	150	0.065	258	357.1	90.2	15.06	0.84	0.431	1725	2315.7	602.5	100.65	5.63
720205	GAMH	7908	1757.6	0.470	1881	296	0.066	265	399.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
720240	GAMH	7909	2071.3	0.470	1881	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
700967	WAAR	7909	2485.1	0.469	1877	226	0.041	162	286.7	34.1	3.36	0.23	0.180	719	1270.5	151.3	14.90	1.03
700973	XHEA	7909	1929.2	0.469	1879	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
701012	CRWU	7909	1533.0	0.469	1879	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	21.12	1.48
656199	XHEA	7909	2350.6	0.468	1873	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1135	2116.5	240.3	11.28	2.87
656221	XHZG	7909	2214.0	0.468	1872	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
741737	VGLZ	7909	1821.1	0.468	1870	246	0.041	165	259.0	28.4	3.51	1.76	0.167	667	1051.4	115.2	14.26	7.13
720137	GAMH	7906	1670.1	0.467	1866	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
720136	CRWU	7901	1570.0	0.467	1867	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	21.12	1.48
701023	GAMH	7909	1789.6	0.466	1862	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
710313	X	7804	1744.1	0.466	1864	0	0.0	0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0
656217	VGLZ	7909	2520.3	0.465	1859	246	0.041	164	259.0	28.4	3.51	1.76	0.167	667	1051.4	115.2	14.26	7.13
720218	GAMH	7909	1857.7	0.464	1856	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
720259	GAMH	7909	2033.7	0.464	1857	296	0.066	265	399.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
656236	LUXC	7909	2461.5	0.463	1854	251	0.040	161	296.0	32.7	1.86	0.57	0.159	638	1169.6	129.1	7.36	2.25
710292	GAMH	7909	1752.9	0.462	1846	296	0.066	265	399.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
720175	GAMH	7909	1919.8	0.462	1848	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
720231	CRWU	7909	1513.5	0.462	1849	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	21.12	1.48
656197	XHEA	7909	2121.6	0.461	1845	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
700974	XHEA	7504	2517.9	0.461	1845	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
720184	GAMH	7909	1802.9	0.460	1841	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
701032	VGLZ	7909	2247.1	0.459	1834	246	0.041	164	259.0	28.4	3.51	1.76	0.167	667	1051.4	115.2	14.26	7.13
720254	FFAN	7909	1624.0	0.459	1836	263	0.047	189	331.7	53.0	3.64	0.36	0.179	716	1259.1	201.1	13.80	1.30
701001	CRWU	7909	1586.2	0.457	1829	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	27.12	1.48
656232	XHZG	7909	2356.0	0.456	1825	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
710317	FFAN	7909	2445.0	0.456	1824	263	0.047	189	331.7	53.0	3.64	0.36	0.179	716	1259.1	201.1	13.80	1.38
731906	MLZL	7909	1569.0	0.456	1824	253	0.079	317	531.7	96.0	9.47	0.84	0.314	1255	2103.8	380.0	37.45	3.34
656218	XHZG	7909	2264.0	0.455	1819	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
750391	XHEA	7909	1234.1	0.455	1821	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
700771	VGLZ	7909	2250.6	0.453	1812	246	0.041	164	259.0	28.4	3.51	1.76	0.167	667	1051.4	115.2	14.26	7.13
720181	GAMH	7908	1950.2	0.453	1813	296	0.066	265	399.8	75.6	6.56	1.08	0.224	894	1350.5	255.2	22.49	3.64
720242	WYID	7909	2089.1	0.453	1811	180	0.036	143	230.4	21.6	1.80	0.60	0.199	755	1281.3	120.1	10.01	3.34
656233	WAAR	7909	2420.4	0.451	1806	226	0.041	162	286.7	34.1	3.36	0.23	0.180	715	1270.5	151.3	14.90	1.03
700959	XHZG	7909	2003.0	0.451	1802	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
710379	GAMH	7909	2120.1	0.451	1803	296	0.066	265	397.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
656213	XHEA	7909	2228.6	0.450	1793	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
700976	XHZG	7908	2539.0	0.450	1800	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
700991	XHZG	7909	2499.0	0.450	1801	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
700980	MHMV	7909	2223.0	0.450	1802	286	0.060	272	503.9	51.5	1.90	0.00	0.238	951	1761.3	179.9	6.66	0.00
700983	XHZG	7909	2256.0	0.449	1795	234	0.053	212	310.2	34.0	2.32	0.95	0.227	909	1326.8	145.5	9.92	4.08
701035	VGLZ	7909	2052.0	0.449	1797	246	0.041	164	259.0	28.4	3.51	1.76	0.167	667	1051.4	115.2	14.26	7.13
720246	MLZL	7909	1564.0	0.449	1796	253	0.079	317	531.7	96.0	9.47	0.84	0.314	1255	2103.8	380.0	37.45	3.34
656243	CRWU	7909	2451.3	0.449	1791	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	27.12	1.48
700942	GAMH	7908	2445.4	0.448	1792	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
720252	CRWU	7907	1675.1	0.448	1794	220	0.069	275	464.4	92.3	5.98	0.33	0.311	1246	2107.2	418.7	27.12	1.48
710326	VSRE	7909	2224.0	0.447	1787	260	0.060	241	419.7	67.4	5.27	0.55	0.232	928	1617.0	259.0	20.31	2.10
720171	GAMH	7909	1824.4	0.447	1787	296	0.066	265	399.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
720214	GAMH	7909	1687.9	0.447	1787	296	0.066	265	399.8	75.6	6.66	1.08	0.224	894	1350.5	255.2	22.49	3.64
700949	XHEA	7909	2436.4	0.446	1783	313	0.089	356	661.4	75.1	3.53	0.90	0.285	1139	2116.5	240.3	11.28	2.87
700964	LUXC	7909	2258.8	0.445	1779	253	0.040	161	296.0	32.7	1.86	0.57	0.159	638	1169.6	124.1	7.36	2.25
656201	GAMH	7909	2106.6	0.444	1776	296	0.066	265	399.8	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64
700740	GAMH	7909	2423.5	0.442	1769	296	0.066	265	399.9	75.6	6.66	1.08	0.224	854	1350.5	255.2	22.49	3.64

TABLE 12

EXAMPLE IAT HISTORY FOR INDIVIDUAL AIRPLANE

OIAIJSLB — DATE: MM/DD/YY

INDIVIDUAL AIRCRAFT SERVICE LIFE RECORD

A/C SSN: 99999999 — MFR SSN: 99999999 — MDS: XXXXXX — CUMULATIVE FLIGHT HRS: 999999 *

CRITICAL C. P. SUMMARY:				
C. P.= XXXXX	DAMAGE= 9.9999 *	FLIGHT HRS= 99999 *	SPECTRUM HOURS= 99999 *	AS OF MMYY
	DAMAGE= 9.9999 *	FLIGHT HRS= 99999 *	SPECTRUM HOURS= 99999 *	AS OF MMYY
	DAMAGE= 9.9999 *	FLIGHT HRS= 99999 *	SPECTRUM HOURS= 99999 *	AS OF MMYY

PREVIOUS MDS: CODE= XXXXXX / DATE= MMYY / FLIGHT HRS= 999999

--- USAGE ---

DATA CAPTURE RATE %	99999 *	TOTAL LANDINGS PREVIOUS QTR	99999 *	TAKEOFF FUEL WT/FLT AVE	99999 *
FLIGHT HRS PREVIOUS QTR	99999 *	TOTAL LANDINGS PER YEAR	99999 *	IN FLT OFFLOAD WT/FLT AVE	99999 *
FLIGHT HRS PER YEAR	99999 *	TAG LANDINGS CUMULATIVE	99999 *	LANDING FUEL WT/FLT AVE	99999 *
AIRFRAME HRS CUMULATIVE	99999 *	TAG LANDINGS PREVIOUS QTR	99999 *	CONTOUR FLIGHT HRS	99999 *
FLIGHTS CUMULATIVE	99999 *	TAG LANDINGS PER YEAR	99999 *	TOTAL REFUEL HRS	99999 *
FLIGHTS PREVIOUS QTR	99999 *	TOTAL PRESSURE CYCLES	99999 *	TOTAL REFUEL EVENTS	99999 *
FLIGHTS PER YEAR	99999 *	TAKEOFF GROSS WT/FLT AVE	99999 *	REFUEL WT/FLT AVE	99999 *
TOTAL LANDINGS CUMULATIVE	99999 *	TAKEOFF CARGO WT/FLT AVE	99999 *		

MISSION MIX PAST QTR — MISSION MIX TOTAL

MISSION #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
% FLT HRS	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
% FLTS	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999	999

--- CONTROL POINT DAMAGE ---

CONTROL POINT:	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
EXPECTED DAMAGE RATE/HR	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *
ACTUAL DAMAGE RATE/HR	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *
CURRENT CRACK LENGTH	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *	9.9999 *
FLIGHT HRS TO LIMIT	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *
SPECTRUM HRS TO LIMIT	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *
SPECTRUM HRS PREVIOUS YR	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *	999999 *
DATE PROJECTED TO LIMIT	MMYY	MMYY	MMYY	MMYY	MMYY	MMYY	MMYY	MMYY	MMYY	MMYY

* ITEMS IN TOP 10%

--- PREVIOUS MAINTENANCE ACTION ---

DATE	ACTION	FLT HRS	DESCRIPTION/REFERENCES
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX

--- RECOMMENDED MAINTENANCE SCHEDULE ---

DATE	ACTION	EQUIV HRS	DESCRIPTION/REFERENCES
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX
YYQ	XXXXXX	999999	(ANY APPLICABLE TEXT MATERIAL)XXXXXXXXXX

--- INSPECTION RESULT SUMMARY ---

DATE	ACTION	FLT HRS	NDE TYPE, NO. OF CRACKS FOUND, MAXIMUM LENGTH, LOCATION, REMARKS
YYQ	XXXXXX	999999	XXXXXXXX(ANY APPLICABLE TEXT)XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
YYQ	XXXXXX	999999	XXXXXXXX(ANY APPLICABLE TEXT)XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
YYQ	XXXXXX	999999	XXXXXXXX(ANY APPLICABLE TEXT)XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

In addition to detailed listings, summaries of the current status provide a quick look capability. Obvious choices for such summaries would be histograms of current damage indices for stratifications of interest. However, another approach is that of Figure 27 which presents a histogram of percent service life remaining.

5.2 TIMES TO MAINTENANCE ACTION

Since maintenance actions will be scheduled in terms of potential crack lengths and planned usage, the data system can be designed to output information regarding the scheduling of maintenance actions. Obviously straight listings of projected dates by tail number or analysis location would provide the data. Other types of presentations can be used to emphasize or summarize.

Table 13 graphically displays a projected inspection schedule for the analysis location of a single airplane. Table 14 represents Lockheed-Georgia's clever method of displaying the projected distribution of number of aircraft that will require the maintenance action during the indicated quarter. The histogram blocks are composed of the manufacturers serial number so that the histogram also indicates the prediction of the precise airplanes which will require the maintenance action.

Figure 28 emphasizes the maintenance action. In this figure the calendar period during which the action will be performed is displayed for each type of action. Obviously the complete distribution rather than the mean and range can be presented at the expense of volume of presentation.

Table 15 is an example of a near term maintenance action summary. The table indicates the actions that will be required for each location and airplane in a given time period.

Mo/Yr.________ Thru Mo/Yr.________

(Force) (MDS) (Command) (Base) (Wing)

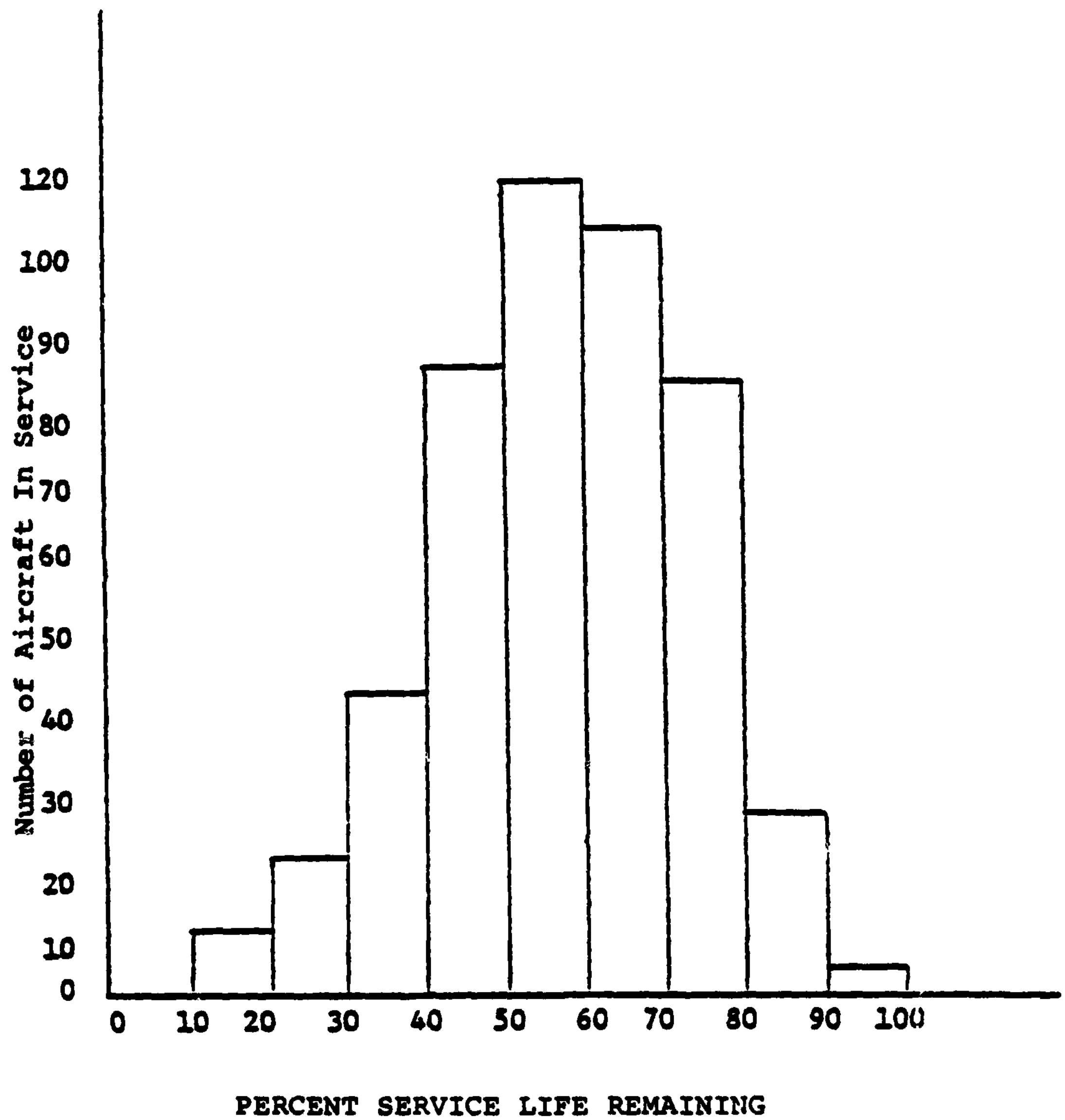


Figure 27. Example of Quarterly Distribution of Aircraft Structural Life Remaining.

TABLE 13

EXAMPLE INDIVIDUAL AIRCRAFT INSPECTION SCHEDULE FOR ANALYSIS LOCATIONS
RANKED BY INSPECTION DATE

Mo/Yr__________thru Mo/Yr___________

(Force) (MDS) (Command) (Base) (Wing)

A/F SER. NO.__________ FLIGHT HRS.___________ TOTAL LDG______________

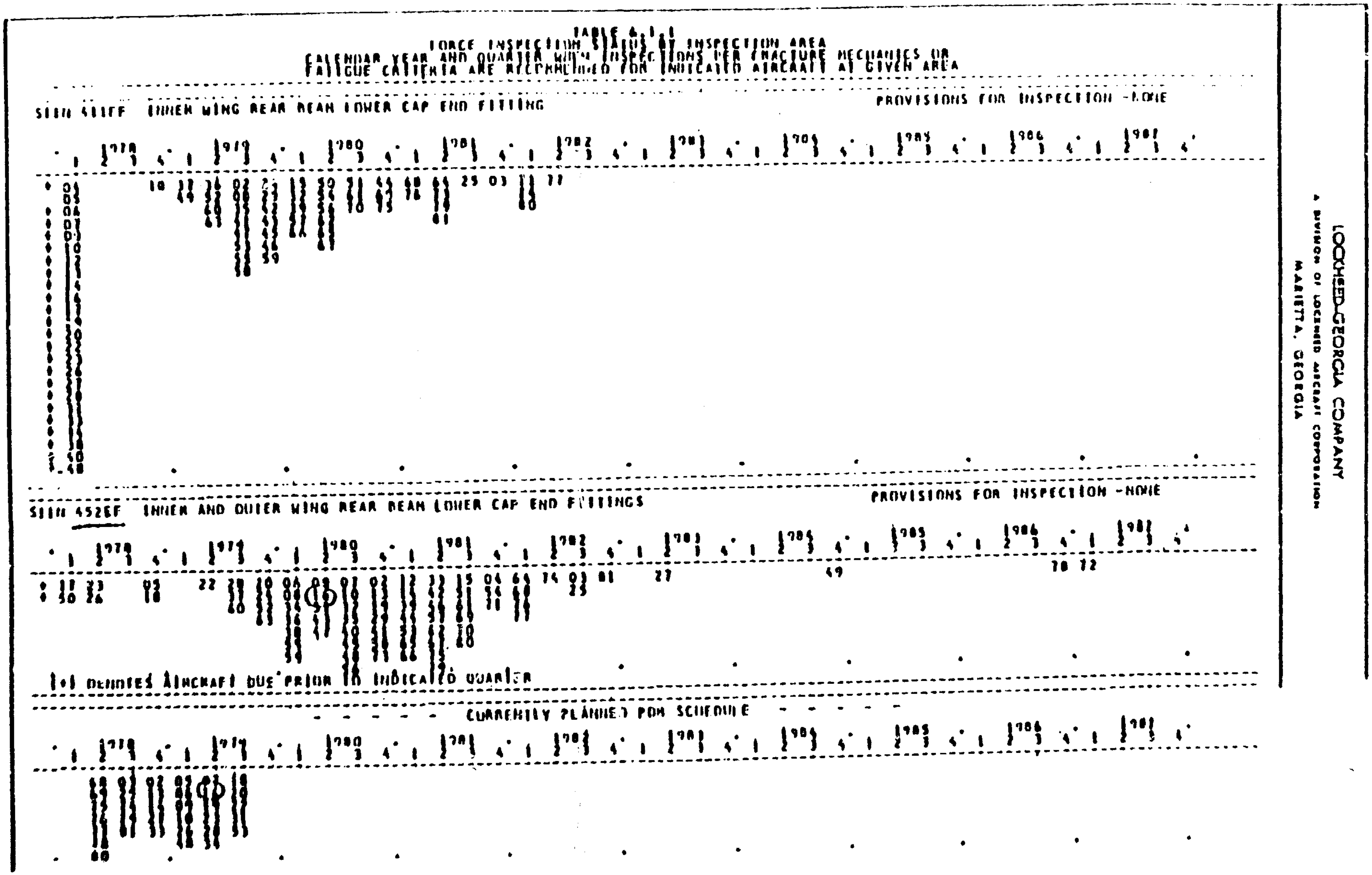
MFR SER. NO.__________ AIRFRAME HRS.__________ FULL STOP______________

TOUCH & GO_____________

ANALYSIS	1980												1981												1982											
LOCATION	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
5	X																																			
3	X																																			
7			X																																	
2				X																																
8						X																														
6								X																												
4											X																									
10											X																									
13													X																							
9															X																					
12																		X																		
1																			X																	
17																					X															
20																							X													
19																									X											
16																											X									
14																												X								
18																																				
15																														X						
11																																X				

TABLE 14

EXAMPLE DISTRIBUTION OF MAINTENANCE ACTION WHICH ALSO INDICATES DATES OF ACTION FOR INDIVIDUAL AIRPLANES



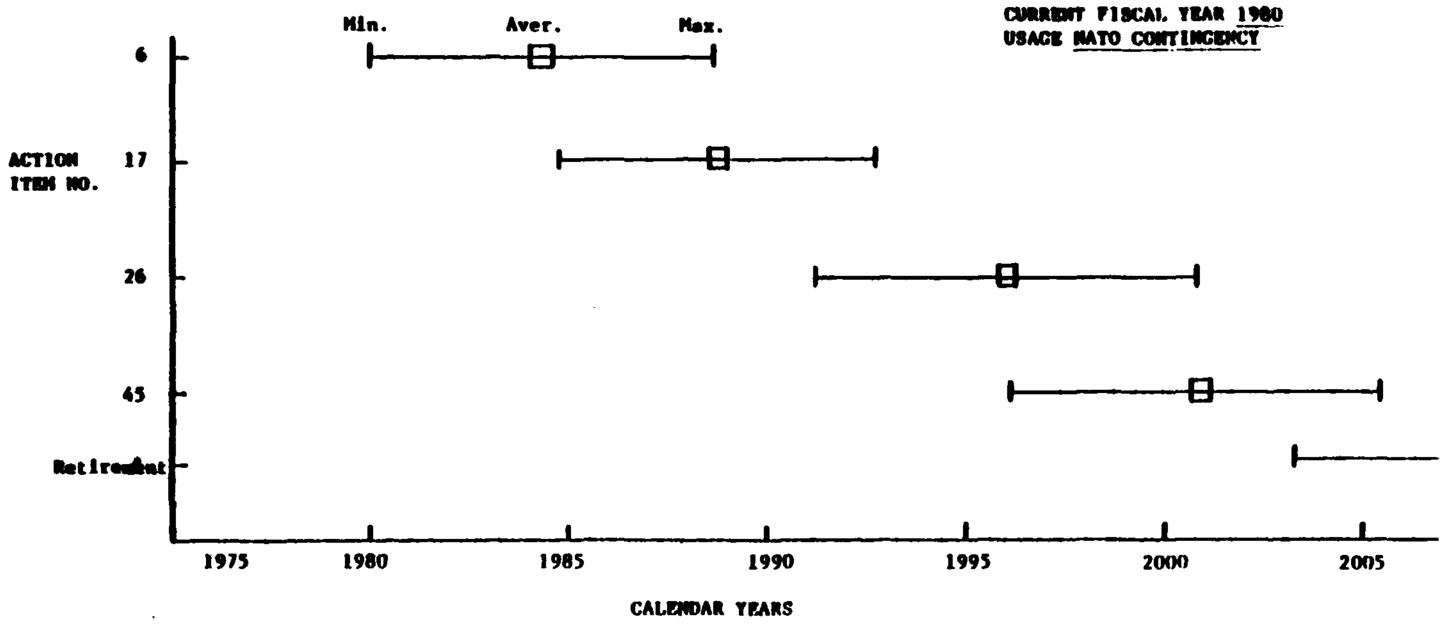


Figure 28. Example Schedule For Maintenance For Various Actions For a Defined Usage Actions Required Prior To Retirement.

TABLE 15

EXAMPLE FISCAL YEAR 1980 INSPECTION PLAN

DATE: ____________________

(Force) (MDS) (Command) (Base) (Wing)

AIR FORCE SERIAL NO.	MFR. Serial NO.	ANALYSIS LOCATION 1	2	3	4	5	6	7	8	9	10	11	12	13	14
660306	2	X			X		X								
660307	5		X		X										
660310	3	X	X		X	X	X								
660322	7	X		X		X									
660421	6					X									
660316	19		X		X	X									
670210	18		X		X		X								
680111	23			X	X		X								
680225	41		X		X		X								
680220	13						X								

5.3 TRENDS IN USAGE

Usage trends have been extensively discussed in the previous sections and their description will depend to a large degree on the available data. If mission data is a part of the IAT or L/ESS functions, then trends in the usage can be described by data tabulations as in the example of Table 16 or in computer generated plot as in the examples of Figures 29 through 32. For selected control locations, usage trends can also be monitored in terms of standardized crack growth (Figure 33) or distributions of calendar times to maintenance actions (Figure 21).

TABLE 16

EXAMPLE TREND ANALYSIS OF MAJOR MISSION PARAMETERS (FOR DERIVED STRATIFICATION)

DATE: ____________________

TOTALS	QUARTERLY SUMMARY						YEARLY SUMMARY BASED ON DESIGNATED 4 QUARTERS				YEARLY SUMMARY (FISCAL OR CALENDAR)			
	Q6 783	Q5 784	Q4 791	Q3 792	Q2 793	Q1 794	Q7-Q4 782-791	Q6-Q3 783-792	Q5-Q2 784-793	Q4-Q1 791-794	1976	1977	1978	1979
Active Aircraft														
Reported														
Planned														
Flight Hours														
% Logged														
Reported														
Ave. for A/C														
Reported for A/C														
Planned for A/C														
Airframe Hours														
Reported														
Ave. Per A/C														
Ave. Per Flight														
Reported Per A/C														
Planned for A/C														
Reported Per Flight														
Planned Per Flight														
Flight Duration														
Ave. Per Flight														
Reported Ave.														
Planned Ave.														
Flights														
Reported														
Ave. Per A/C														
Reported Ave.														
Planned Ave.														
Landings-Total														
Reported														
Ave. Per A/C														
Ave. Per Flight														
Reported For A/C														
Planned Per A/C														
Reported Per Flight														
Planned Per Flight														

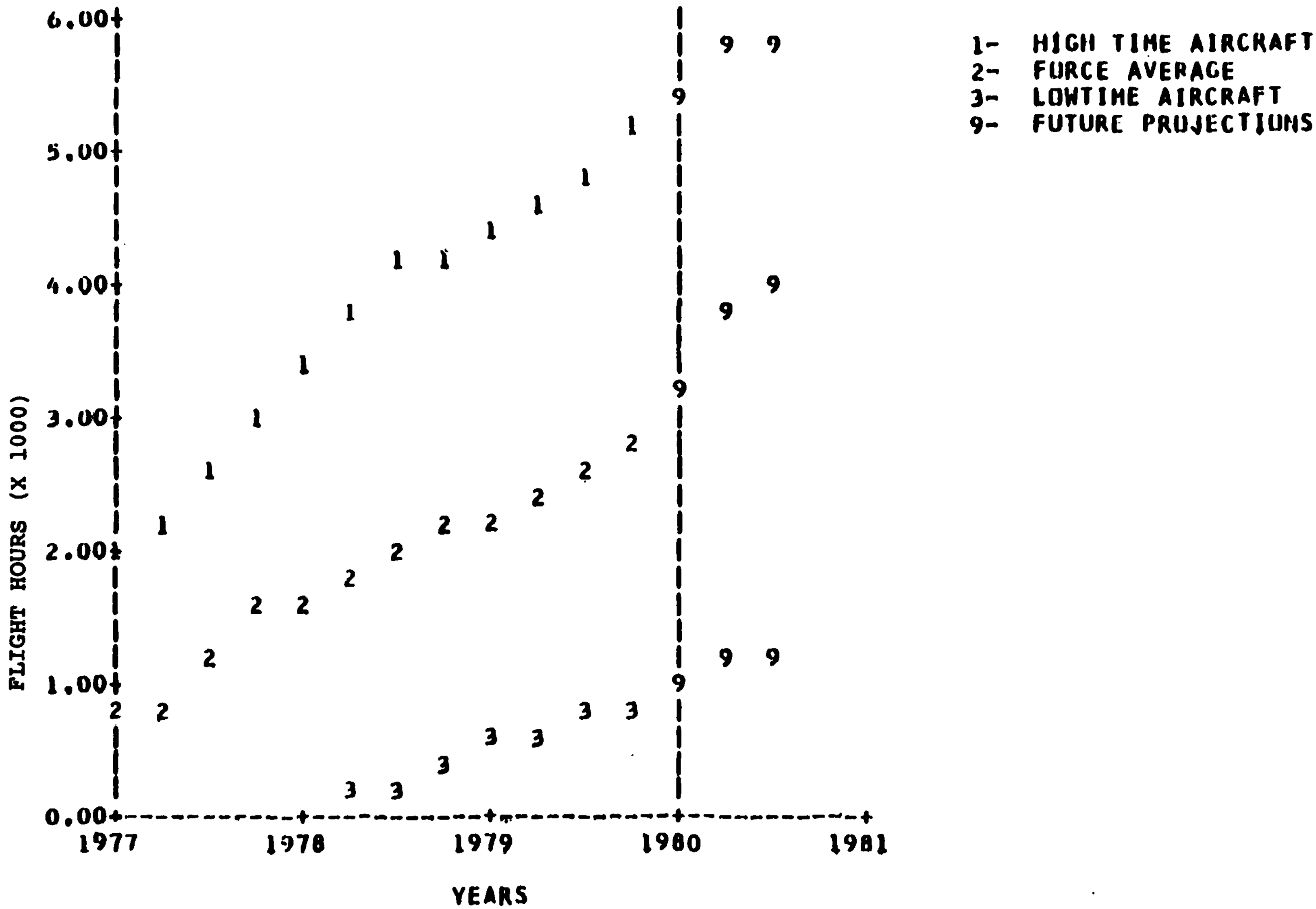


Figure 29. Example Cumulative Flight Hours Per Aircraft.

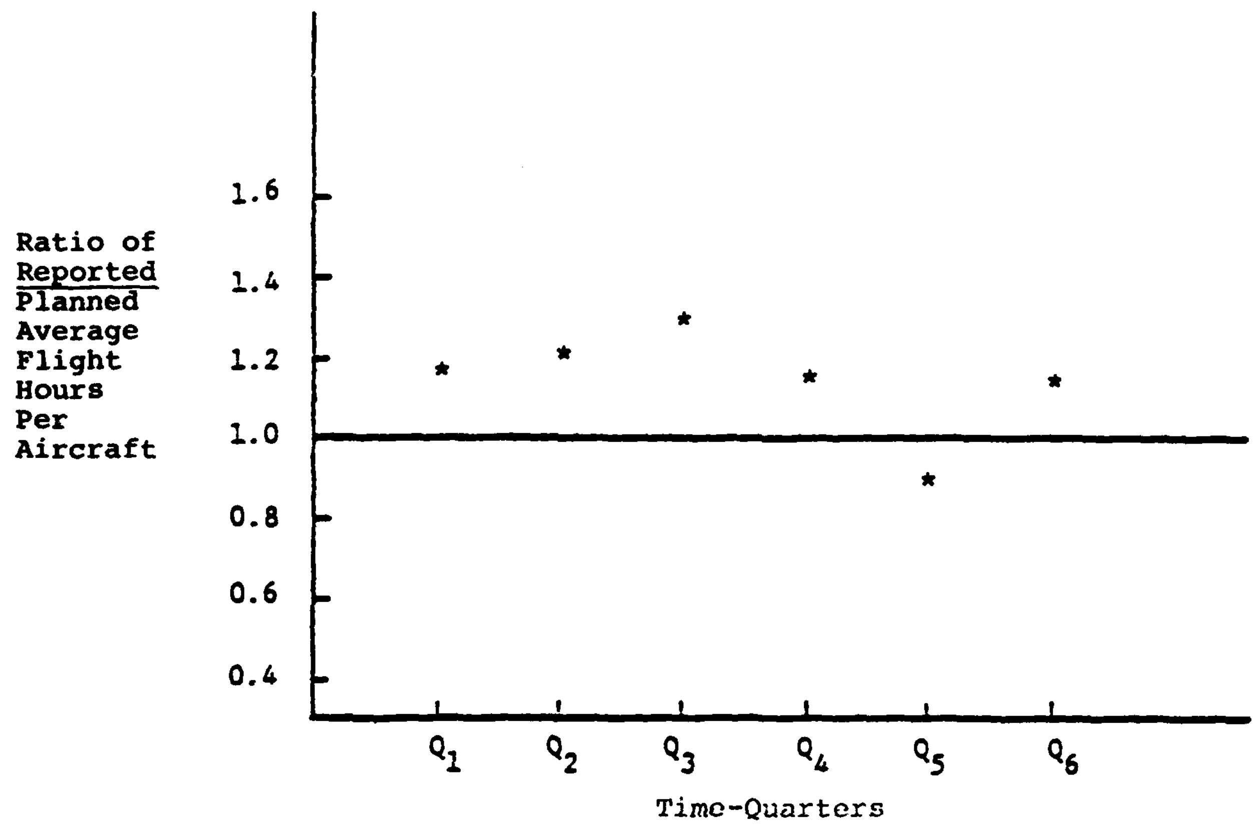


Figure 30. Example Ratio of Reported/Planned Average Flight Hours Per Aircraft for Six Quarters.

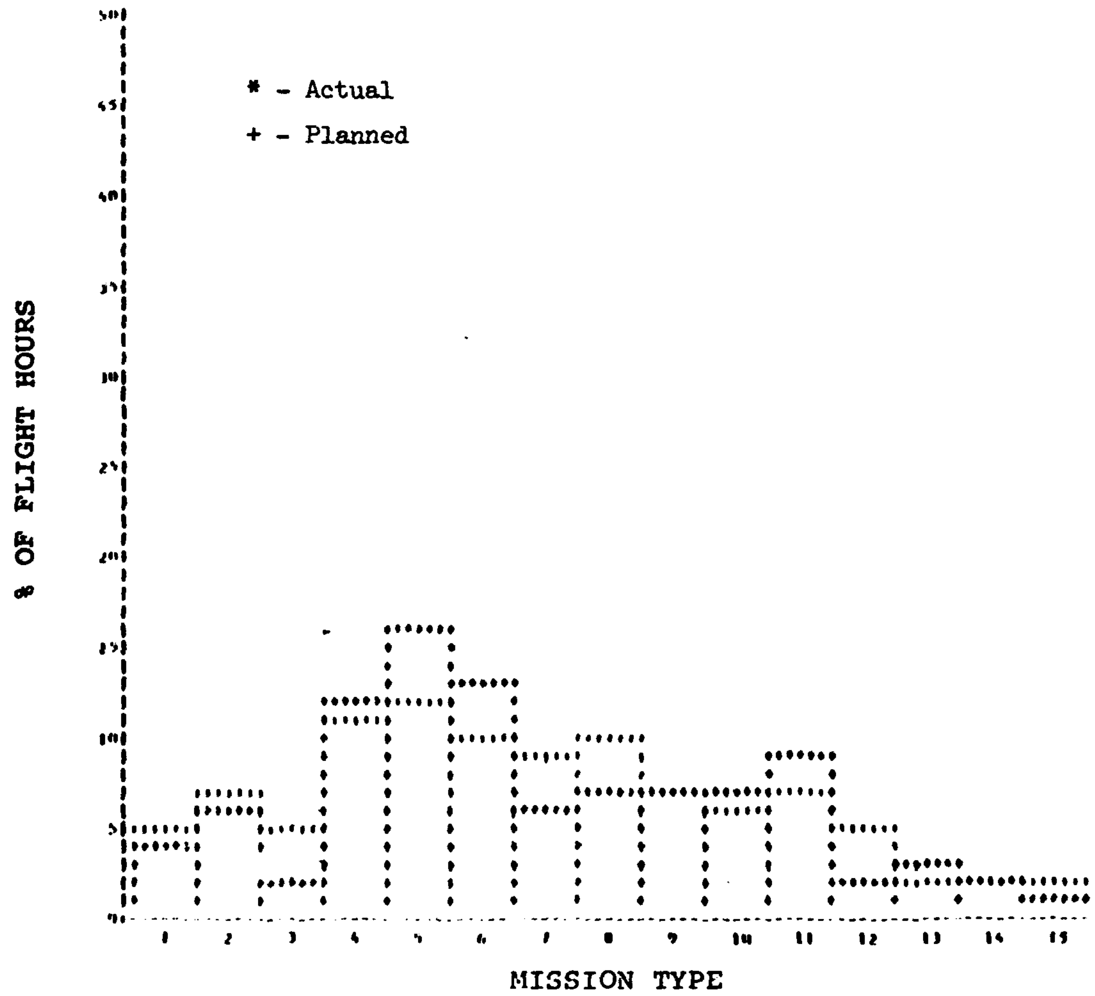


Figure 31. Example Distribution of Flight Hours by Mission Type.

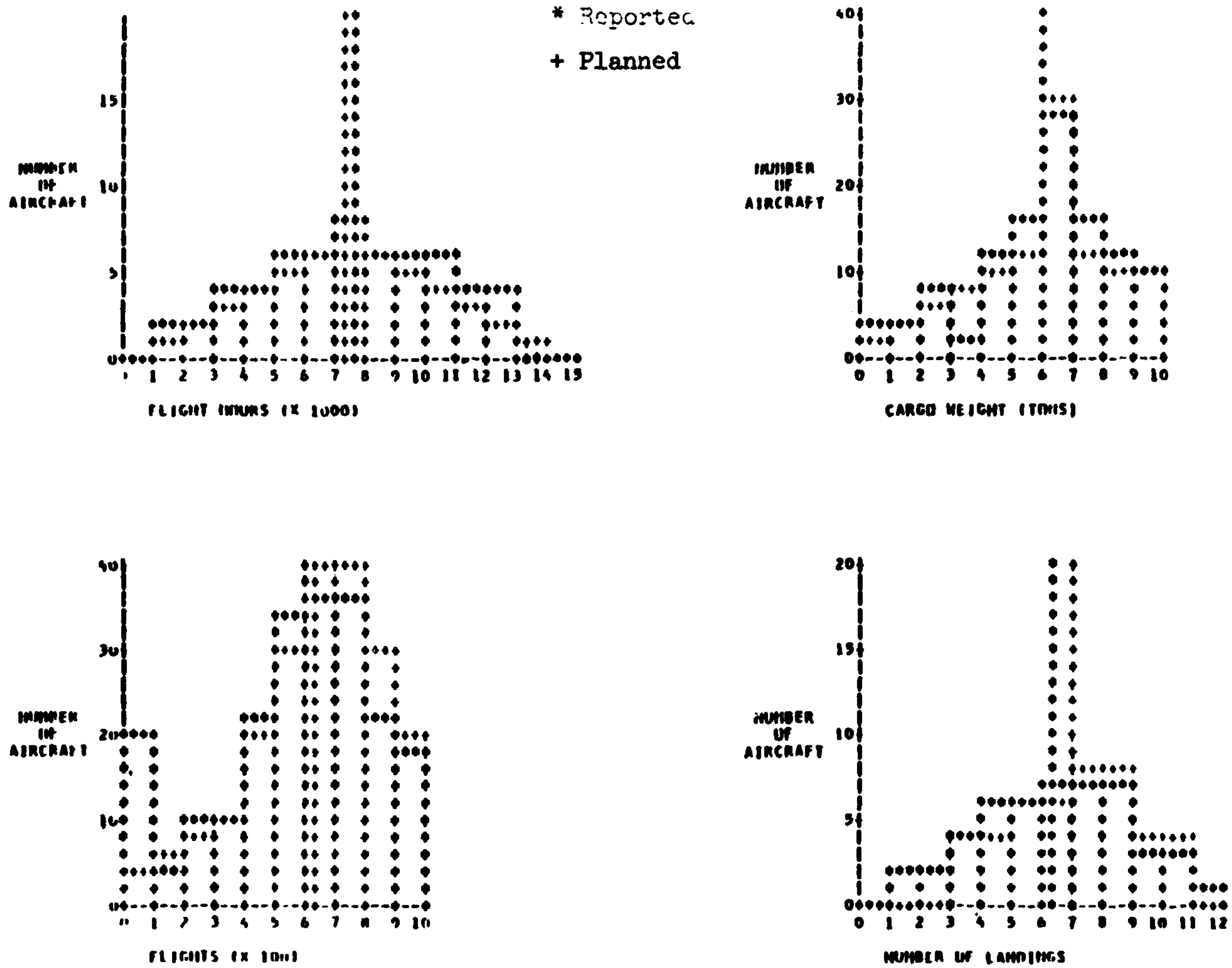


Figure 32. Example Summaries of Mission Parameters.

DATE: ____________

(Force) (MDS) (Command) (Wing) (Base)

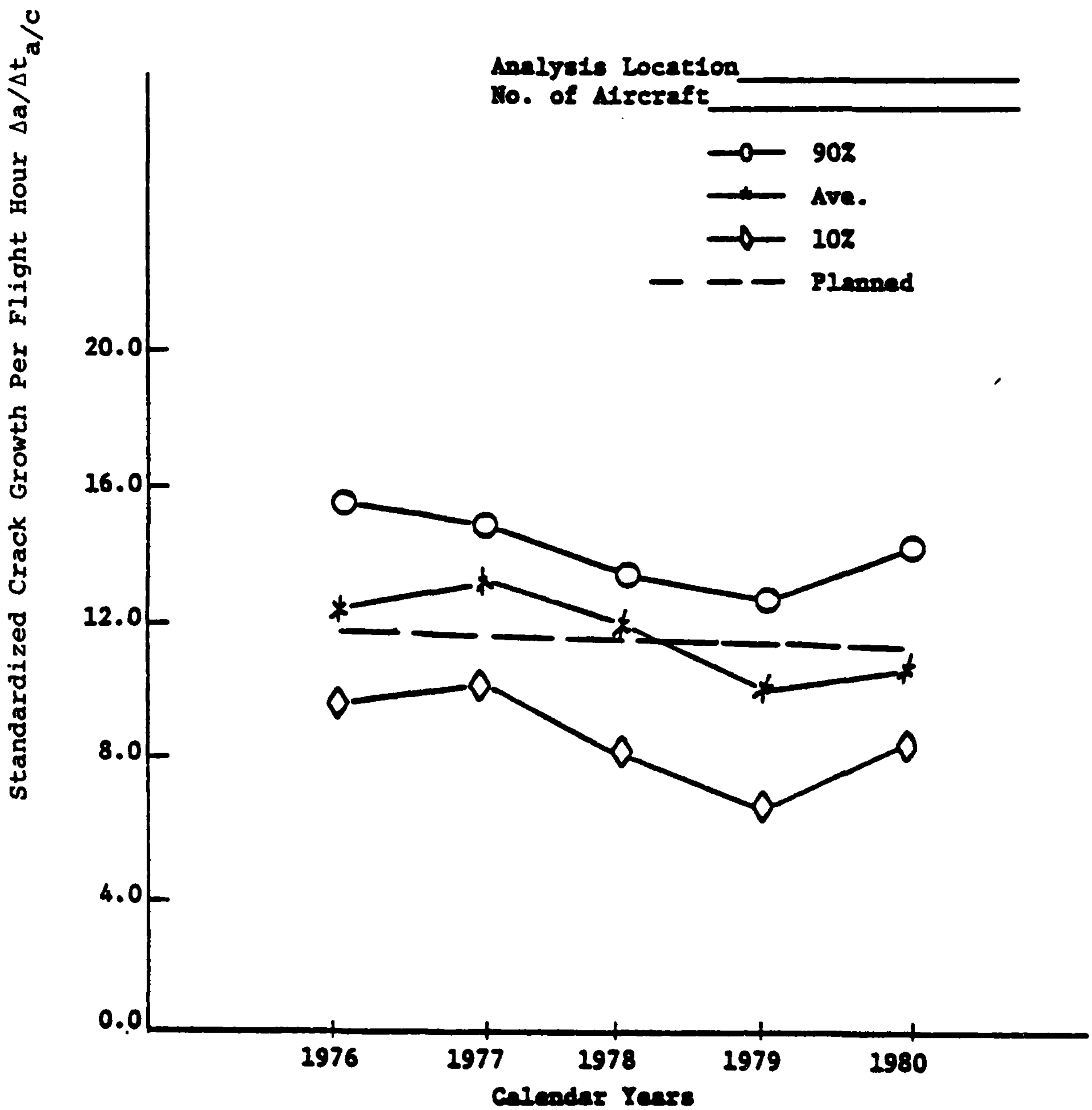


Figure 33. Example Average Standardized Crack Growth Rate Versus Calendar Years.

SECTION 6
SUMMARY AND CONCLUSIONS

The analyses performed by the University of Dayton during Task 2 of the program were devoted primarily to error analyses in the IAT function, sample size requirements in L/ESS and usage change detection. IAT accuracy was defined in terms of the appropriate analytical crack growth model. An analysis method was formulated for the random errors associated with predicted calendar times for a potential crack to reach critical size. A parametric analysis based on recent data from an attack/fighter/ trainer aircraft indicated that large random errors are possible. For maintenance action scheduling, more than 5 groupings would be unwarranted.

Models were formulated for quantifying errors in potential crack length when the IAT function is being accomplished from forms and by cycle-by-cycle stress computations. In the forms (flight log) error model, the variation in potential crack length estimates would be estimated from an aircraft (location) specific crack growth equation and operational stress histories observed during the L/ESS program. The variation in crack length estimates using the cycle-by-cycle model results from the random error associated with stress transfer and can easily be estimated. It was shown that a significant bias error could result from the cycle-by-cycle calculation method if the correlation between stress at two locations is not very high.

A model was formulated for statistically evaluating the quantity of data required (or available) in the L/ESS function. The model is based on a standardized crack growth metric in which it is assumed that the same potential crack size is present in all flights (or excursions into a flight condition). The input required to apply the model could be obtained as a routine L/ESS output.

Usage change detection was defined as being a change in operations, a change in stress magnitudes encountered, or a change in rate of occurence of significant stresses. A method was postulated (with examples) for detecting changes from IAT data and an approach was outlined which would permit usage change detection without multichannel L/ESS type data.

An analysis of the objectives of the L/ESS function indicated that, in general, it is not necessary to collect and process multichannel loads data from 10 to 20 percent of a force on a continuous basis. After the initial L/ESS, the objectives can be met using the data of the IAT program, periodic analysis of auxiliary data, and, perhaps, limited data from new operations. If a usage change is of sufficient magnitude that it requires a new DADTA, its occurrence will be known and a complete new L/ESS will be justified. Therefore, it is recommended that the L/ESS should last only through the data collection period required for the initial evaluation of the design load sequences and the and the update of the initial DADTA. To perform the L/ESS on a continuous basis throughout the life of a force should require special justification based on that aircraft's data requirements.

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